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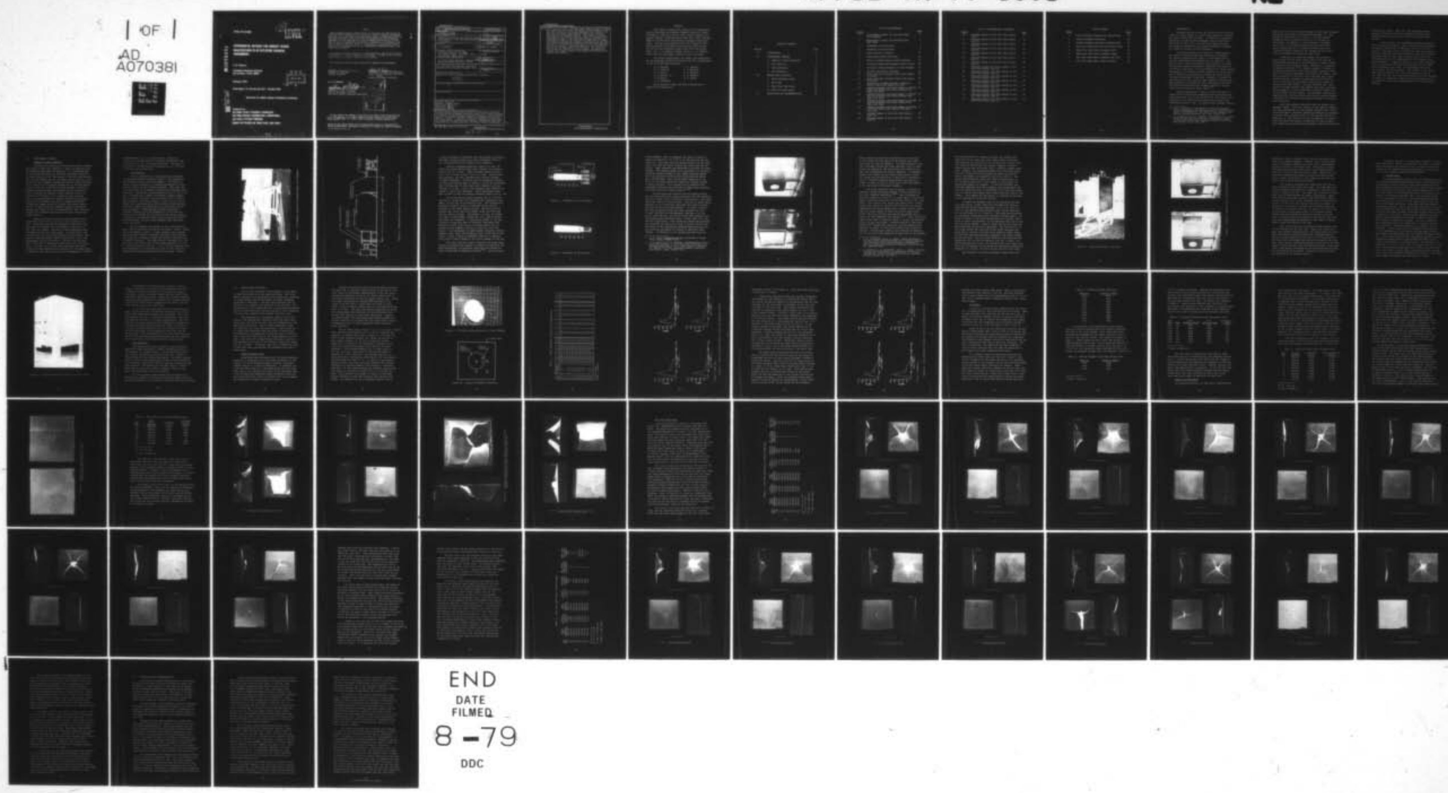

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EXPERIMENTAL METHODS FOR AIRCRAFT DESIGN QUALIFICATIONS IN AN EXPLODING WARHEAD ENVIRONMENT

E. D. Esparza

Southwest Research Institute
San Antonio, Texas 78284

February 1979

Final Report for Period July 1977 - October 1978

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An experimental program was performed to investigate the effect of high-velocity fragments alone and coupled with a blast pressure to determine whether accurate simulation testing of aircraft fuel tanks in a near-miss exploding warhead environment must include the blast threat. A series of tests was conducted to synchronize the fragments and blast pressure loading. Experiments were then conducted using a simulated fuel tank which included replaceable over

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20. front and rear walls. The fuel tank, empty and full of water, was tested with five steel rectangular prism fragments alone, and the combination of the same fragments with a blast pressure wave of similar magnitude and duration as would be generated by an exploding warhead. Four types of aluminum front panels were tested using two types of aluminum and two thicknesses of each. The rear panel used on the full tank tests was the same for all these tests. The report presents the complete experimental program, a description of the test facilities, the simulation techniques and the instrumentation used in the program. Structural damage to the test panels are depicted by photographs of each panel. The results indicate that the addition of blast pressure can definitely enhance the fragment damage to the panels, particularly with an empty fuel tank.

PREFACE

This report presents the results of an experimental program performed by Southwest Research Institute (SwRI), San Antonio, Texas for the Air Force Flight Dynamics Laboratory (AFFDL), Wright-Patterson AFB, Ohio, under Contract DAAK11-77-C-0043 from the Ballistics Research Laboratory (BRL). The work was funded by the Joint Technical Coordinating Group for Aircraft Survivability under Project No. TF-7-15 and performed between July 1977 and October 1978. Mr. C. L. Anderson (AFFDL) and Dr. C. E. Anderson (BRL) were the government technical project managers.

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I. INTRODUCTION

Warheads from air-to-air and surface-to-air missiles present a severe threat to aircraft survivability even when the missile misses the aircraft. In particular, proximity detonation of anti-aircraft warheads, which occurs more often than a direct hit, can critically damage aircraft fuel tanks by penetration of multiple high-speed fragments and transient loading of blast pressure.

To develop concepts and designs to defend against the threat of near-miss warhead explosions, techniques for testing simulated fuel tanks, a high-hazard area to aircraft survivability/vulnerability, are required. Full scale tests of even single-engine type aircraft, in which the fuselage tankage surrounds or straddles its centrally located air inlet duct, are very expensive and time-consuming. Consequently, multi-test programs required to conduct parametric studies to characterize fragment and blast threats are almost impossible to perform. Instead, to assess the vulnerability of fuel tanks to such threats, programs have been conducted to develop and test techniques to simulate the missile-related multiple fragment threat[1] and the associated near-miss air blast threat.[2]

Because penetration of the air inlet duct wall of single-engine aircraft by fragments from an exploding warhead would cause fuel to be ingested into the engine, this mechanism can be sufficient to cause engine failure and subsequent aircraft loss. To simulate this fragment threat,

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1. Paul M. Murawski, "Development of Multiple Fragment Launch Capabilities and Determination of Impact Effects," Report 61 JTCG/ME-77-8, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, August 1977.
2. E. D. Esparza and A. B. Wenzel, "Development of a Blast Simulator for Testing Simulated Aircraft Fuel Tanks," Report JTCG/AS-76-T-004, Southwest Research Institute, San Antonio, Texas, July 1978.

sabots and a dual-barrel launch weapon (30 mm) were designed, fabricated and tested as described by Murawski.[1] This system can launch up to 18, 0.55 oz (15.6 gm) compact fragments with an average velocity of up to 6000 fps (1829 mps). In addition, a tank designed to simulate the volume of an actual fuselage fuel tank was used to obtain comparison data on fragment effects using this relatively simple, versatile and inexpensive test technique as compared with actual warhead tests.

Generally, to assess the damage contribution of blast as part of the total threat effect from the near-miss warhead detonation is very difficult in actual combat incidents as well as arena tests. Therefore, as reported by Esparza and Wenzel,[2] a chamber capable of generating variable pressure-time blast loads against simulated fuselage fuel tanks was developed, calibrated and tested. Peak blast pressures of 10-50 psi (69 to 345 kPa) and corresponding specific impulses of approximately 60-150 psi·ms (414 to 1034 kPa·ms) were used to test several types of aluminum fuel tank panels. Results indicated that, even with the highest pressure and impulse load used, the blast threat alone will cause significant structural damage only to very light, brittle panels. The permanent deformations experienced by the more ductile and thicker aluminum panels tested are not a serious survivability problem to aircraft fuel tank walls.

The blast pressure wave will load the target after fragment impact. Thus, the effects of the combined loading has been investigated (in the program reported here) using the multifragment launching technology developed in Reference 1 and the blast simulator built in the program reported in Reference 2. The objective of this program was to investigate and assess the damage contribution of blast loading when synchronized with multiple fragment impacts on simulated

fuselage fuel tanks. This will then determine whether accurate simulation of missile warhead near-miss detonations against simulated fuel tanks must include blast effects.

In this report, the experimental program conducted will be covered in detail. This program included extensive preliminary testing for calibration as well as the main testing. The main testing consisted of tests using empty and full simulated fuel tank conditions with four different configurations of front impact panels loaded with five fragments only and the combination of five fragments and blast pressure. A complete summary of the tests conducted will be presented along with a description of the experimental apparatus, the tests, the instrumentation used, and the data reduction process. The results of the entire test program together with still photographic views of the front and rear fuel tank panels tested will be discussed. A summary of significant observations and conclusions will be presented as well as recommendations for future investigations.

II. EXPERIMENTAL PROGRAM

Summary of Tests Conducted

To achieve the objective of this experimental program, two types of tests were conducted. First, an extensive set of 54 preliminary tests was required (1) to establish that an off-center detonation in the blast simulator produced a pressure loading on the front panel of the fuel tank similar to a central detonation (an off-center charge location is required to allow fragment passage through the blast simulator); (2) to test the 30 mm weapon assembly which included proper aiming of the gun, locating the sabot stripper, obtaining desired fragment spread, and determining the propellant load to produce the desired average fragment velocity of 4,500 fps (1,372 mps); (3) to ascertain that the foam used in the blast simulator chamber would have negligible effect on the fragment velocity as fragments travelled through the chamber prior to striking the target plates; and (4) to synchronize the combined fragments and blast loading such that a delay of approximately 3 msec occurred between the fragments striking and the blast loading the target plates.

Second, the main set of data tests consisted of 33 experiments using both an empty and full simulated fuel tank. Fragments alone and in combination with blast load were used to determine the contribution of the blast on fuel tank wall damage. Sixteen of these experiments were conducted with the fuel tank empty. In these tests, only the front wall of the tank was required to be tested. Two types of aluminum panels, 2024-T3 and 7075-T6, and of two thicknesses, 0.073 and 0.040 in. (1.80 and 1.02 mm) were used. The other 17 experiments were done with a full fuel tank. A similar set of front fuel tank panels was used in the full tank experiments as was done for the empty tanks. In addition, the rear wall of the tank consisted of a 2024-T3

aluminum panel, 0.1 in (2.54 mm) thick, interiorly lined with a bladder material (Goodyear XA22A440-Y) fabricated to U. S. Air Force specifications. The water in the tank was pressurized with regulated air to 1.15 psig (7.93 kPa) during each test.

Test Facility

All the experiments of this study were conducted at Southwest Research Institute (SwRI) in the Explosives and Ballistics Range located on-campus. This facility, though easily accessible, is located approximately a mile from the center of the Institute complex. This range has the flexibility for conducting several test programs simultaneously. Detonation of bare explosives up to 3 lb_m (1.36 kg) is allowed and a number of different caliber weapons such as 20 mm, 26 mm and 30 mm have been fired in various past projects. For this project, a 30 mm x 8 ft (2.44 m) smooth bore tube supplied by the Air Force Flight Dynamics Laboratory (AFFDL) was modified at the Institute for use on this project. Modifications included machining of mounting grooves and firing chamber for 30 mm case, and threading the chamber end for mounting the action assembly. In addition, the mounting blocks, mount stand with recoil shock absorbers, and the action assembly were fabricated at the Institute.

The gun assembly was mounted on one of the concrete pads used for ballistic testing at the range. Figure 1 shows the 30 mm weapon in place. A sabot catcher plate, chronograph velocity screens, the blast simulator, the simulated fuel tank and a fragment catcher were setup on the test pad as shown in Figure 2. The sabot catcher consisted of a 1-in (25.4 mm) thick steel plate located approximately 6 ft (1.8 m) from the muzzle of the gun. A 4-in (102 mm) diameter hole was determined to be sufficiently large to allow the five separating fragments through and stop the sabot. Several

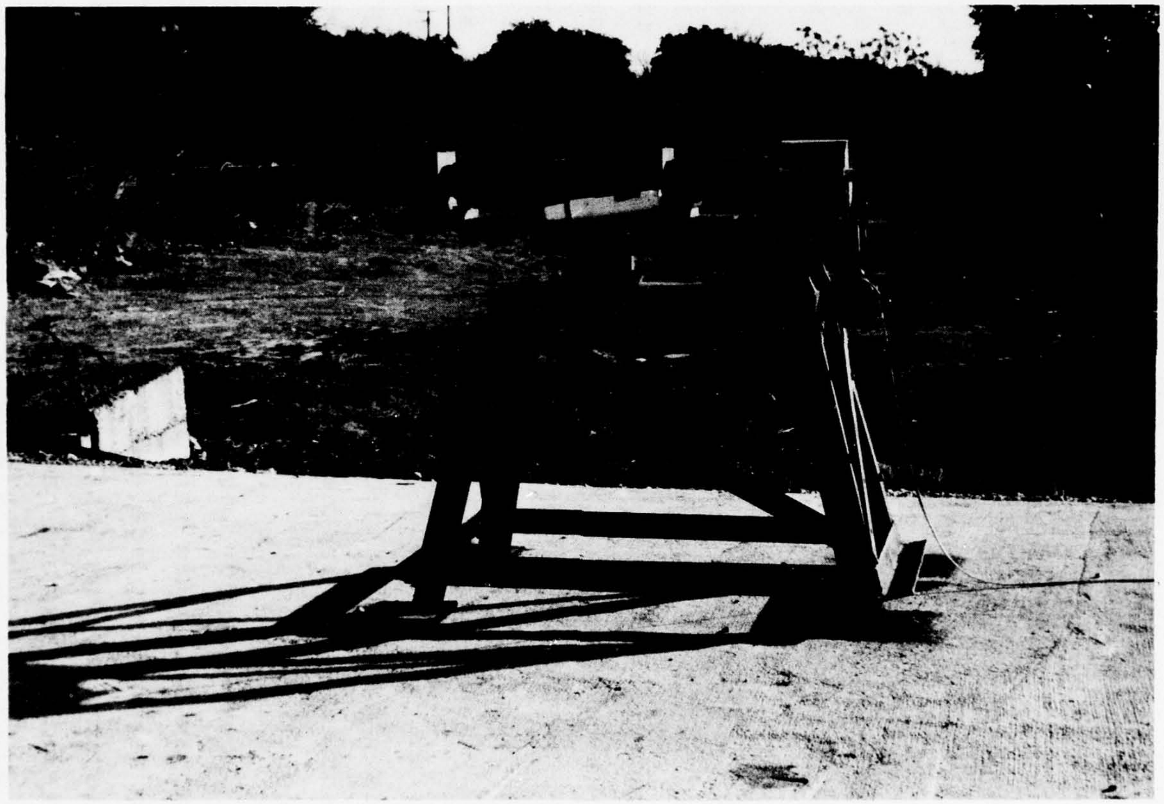

Figure 1. 30 mm Weapon System for Launching Sabot and Fragments

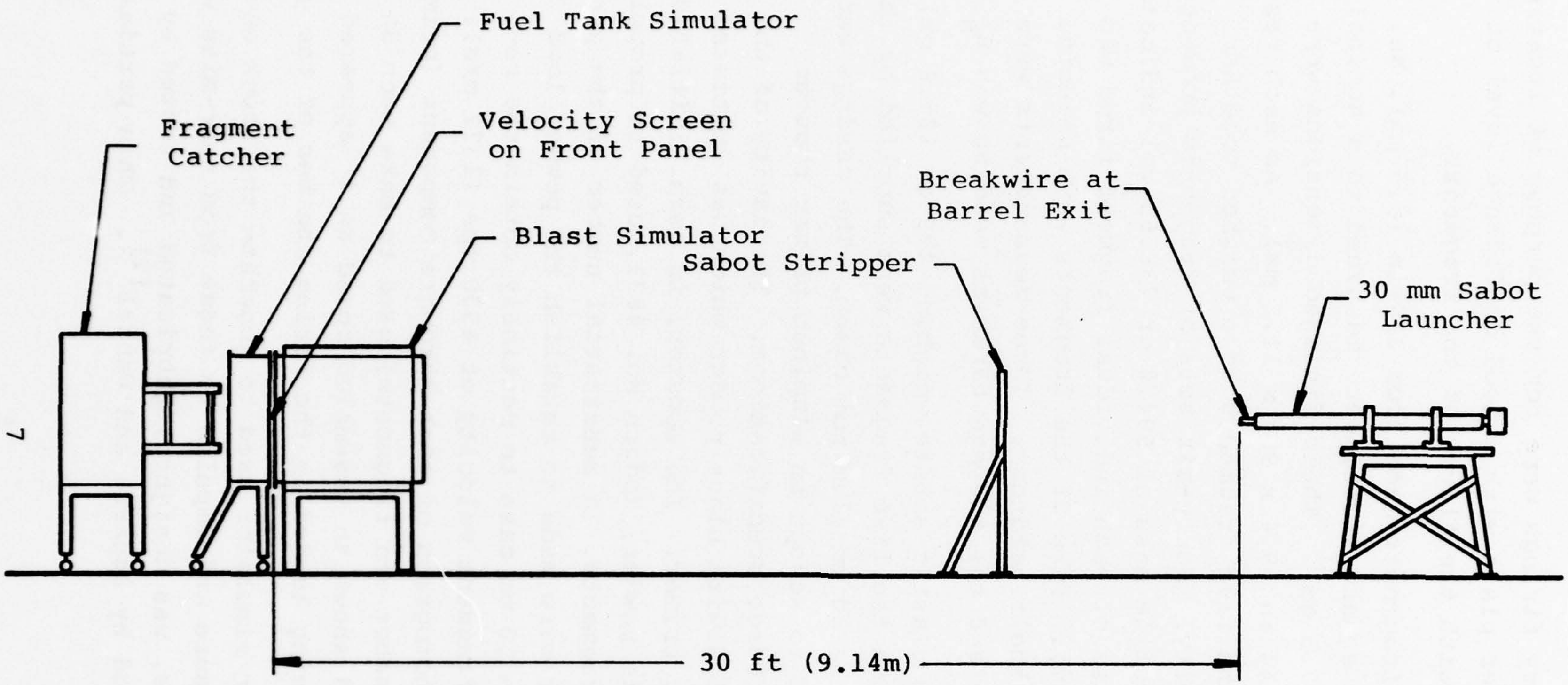

Figure 2. Experimental Layout for Simulated Fuel Tank Tests

of the preliminary firings were for the purpose of locating the sabot stripper plate with a good confidence level of not interfering with the flight of the fragments.

The five fragments made from 3/8-in (9.5 mm), No. C1018 cold drawn square stock, were machined to a nominal mass of 120 gr (7.8 gm). Their finished dimensions were 0.37 x 0.37 x 0.44 in (9.4 x 9.4 x 11.2 mm). As each test was conducted, the five fragments were weighed together to check uniformity. Forty-six sets of fragments produced an average projectile mass of 594.6 gr (38.63 gm) indicating that the mean mass of each individual fragment fired was 118.9 gr (7.71 gm). Five of the fragments were selected at random to check their hardness. Three measurements were made on each one and the average hardness reading was $R_B = 95$.

The 30 mm plastic sabots weighing 429 gr (27.8 gm) and used to launch the five fragments were supplied by the AFFDL, as were the 30 mm aluminum cases. The casings were modified at SwRI to accept an aluminum primer booster machined to Air Force specifications. The cavity of the booster was filled with black powder which was initiated with an electric primer. The booster, in turn, initiated the load of rifle powder, Hodgon No. 4831, used to propel the sabot and fragments. A substantial number of the preliminary firings were made to establish the powder load required in each 30 mm case to routinely obtain the required average fragment velocity of 4500 fps (1372 m/s). Figure 3 is a photograph of each hardware component (primer, booster, case, sabot and fragments) used to make each 30 mm round. Figure 4 shows an assembled round as it appeared just prior to being loaded in the firing chamber of the gun.

The blast simulator used to generate the shock waves, similar in pressure and impulse to those from near-miss warhead detonations, was designed, fabricated and tested by SwRI as described by Esparza and Wenzel[2]. This partially

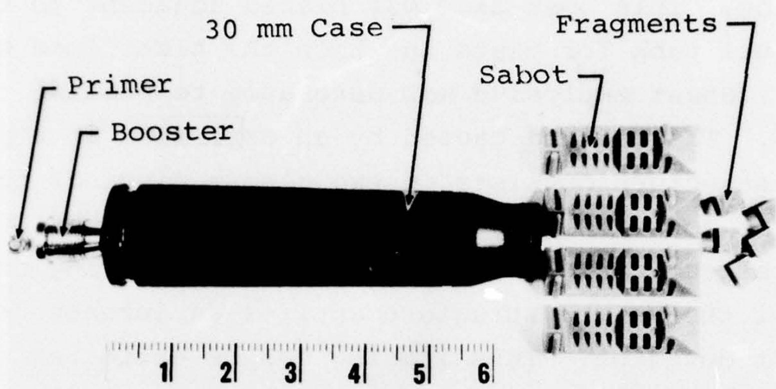

Figure 3. Components of 30 mm Round

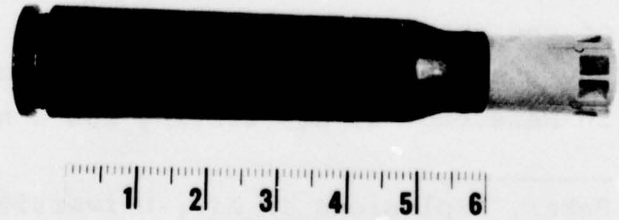

Figure 4. Assembled 30 mm Cartridge

vented chamber, cubic in geometry and shown in Figure 5, measures internally 3 ft (0.91 m) on the side and has one open side. This open side was placed adjacent to the simulated fuel tank for tests in which the blast load was required. Sheet explosive was detonated to provide the blast loading. The loading caused by an explosion in a partially vented structure consists of two almost distinct phases. The first consists of the initial blast wave and subsequent reflections. This initial shock impinging on the walls of the vented structure applies an intense loading of short duration. This loading can be estimated with reasonable accuracy from test data of blast waves normally reflected from rigid, plane surface.[3,4]

As the blast wave reflects and re-reflects within the structure and as the energy available from the explosive source is added to the air within the structure, a gas pressure rise occurs in the structure. This gas or quasi-static pressure is of a much lower amplitude and longer duration than the initial reflected pressure. In order to obtain the desired pressure profiles, peak pressures of up to 50 psig (345 kPa) and corresponding impulses up to 150 psi·ms (1034 kPa·ms), the initial blast peak pressure and reflections were attenuated using a light, open cell foam over the test plates. This technique lowered the amplitude and stretched the duration so that it would coalesce with the decay of the quasi-static pressure whose duration was controlled by the amount of venting in the cubic blast chamber. In Reference 2, all testing was done with the

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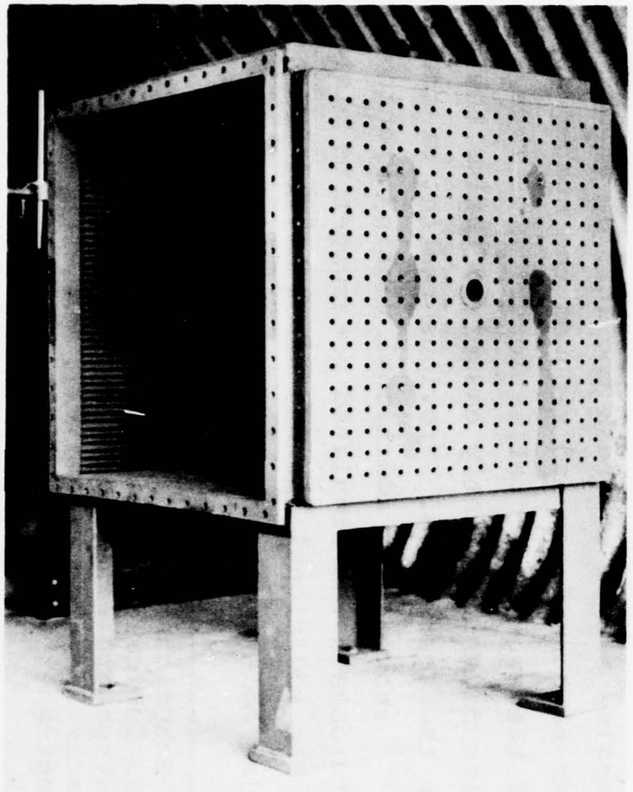
3. W. E. Baker, Explosions in Air, University of Texas Press, Austin, Texas, 1973.

4. A. B. Wenzel and E. D. Esparza, "Measurements of Pressures and Impulses at Close Distances from Explosive Charges Buried and in Air," Final Report on Contract No. DAAK02-71-C-0393, Southwest Research Institute, San Antonio, Texas, August 1972.



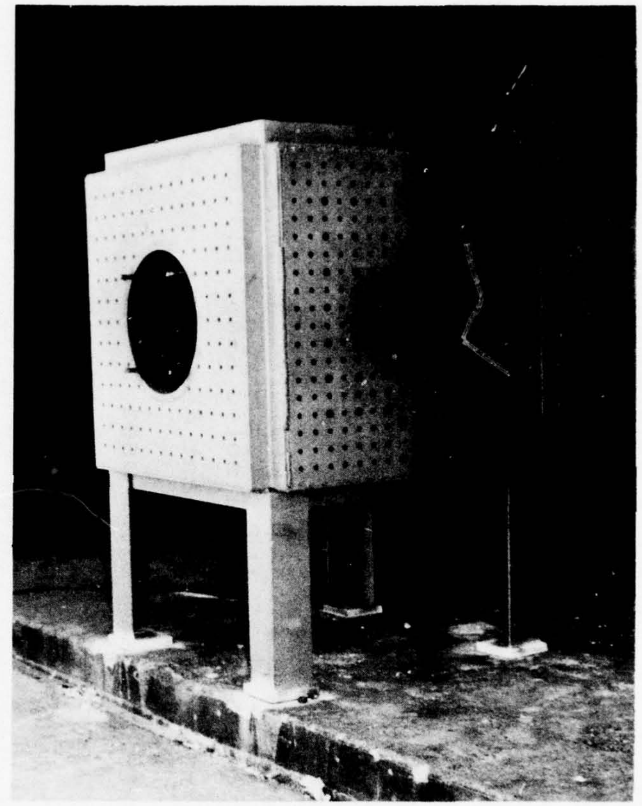


Figure 5. Blast Simulation Chamber

sheet explosive positioned perpendicular to the target on the center vertical plane of the chamber and, thus, there were two axes of symmetry. To allow passage of the five fragments through the blast simulator prior to detonating the explosive, the charge had to be moved to one side thus eliminating one axis of symmetry. To determine whether the loading on the target plate would or would not change significantly due to this shift in charge location, reflected pressure measurements were made on a number of tests in which a solid steel plate was bolted on the open face of the blast chamber.

The blast simulator used is similar in design to uniformly vented structures tested in scale model by the Ballistic Research Laboratory.[5,6] The five sides of the blast simulator consist of an inner layer of structural angles uniformly spaced and a perforated plate as the outer layer. This double layer design was chosen over a single vented plate primarily because test data from the similar suppressive structures showed that a closed, evenly spaced layer of angles seemed to break the initial shock wave better than flat surfaces and reduced the number and intensity of the subsequent reflections.[5,6] Thus, the double layer design made it slightly easier to tailor the pressure profile on the test plate. Previous testing of the blast simulator[2] showed that additional venting openings were required to obtain the simulated pressure-time histories desired. The additional opening was achieved by enlarging the circular hole side opposite the open face of the chamber.

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5. R. M. Schumacher and W. O. Ewing, "Blast Attenuation Outside Cubical Enclosures Made Up of Selected Suppressive Structure Panel Configurations," BRL-MR-2537, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1975.

6. C. Kingery, R. N. Schumacher, and W. O. Ewing, "Internal Pressure from Explosions in Suppressive Structures," BRL-IMR-403, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1975.

This made shooting of fragments through the chamber much easier and at the same time, the longer loading durations were achieved by simply partially closing this circular area. This modified design made the chamber resemble a cubicle vented through one side rather than a uniformly vented structure. However, the venting provided by all the sides along with the internal angles decreased the shock reflections within the chamber (as opposed to solid flat walls). The angles and perforated plates were sized conservatively so the repeated loads from a large number of tests would not appreciably damage the chamber. In the two different test programs conducted using this chamber, only minor damage has been inflicted primarily to some welds on the interior angles and to a few of the outside plate welds along the frame of the chamber. This damage was repaired as it occurred to preclude a more detrimental structural failure.

To apply the pressure load on the simulated fuselage fuel tank skins, a steel frame with the same size interior cross-section as the blast simulator, 3 ft x 3 ft (0.91 m x 0.91 m), was designed and fabricated with a depth specified by the Air Force of 1 ft (0.305 m). This tank has provisions for accepting replaceable front and back aluminum panels. As shown in Figure 6, the frame was mounted on a rollable steel stand to allow easy movement of the simulated fuel tank to and from the blast chamber. Figure 7 shows how the fuel tank was positioned next to the blast simulator. The flat surface of the flange around the open side of the blast simulator was lined with a 1/2-inch (12.7 mm) thick neoprene rubber gasket and the fuel tank was externally clamped to the blast chamber during the tests. The fuel tank frame was also provided with connections for filling and emptying the tank of water, for monitoring the water level, for measuring the inlet water flow rate, and for applying to the water the specified regulated air pressure of 1.15 psig (7.93 kPa) during the full tank tests.

The simulated tank with replaceable square walls was

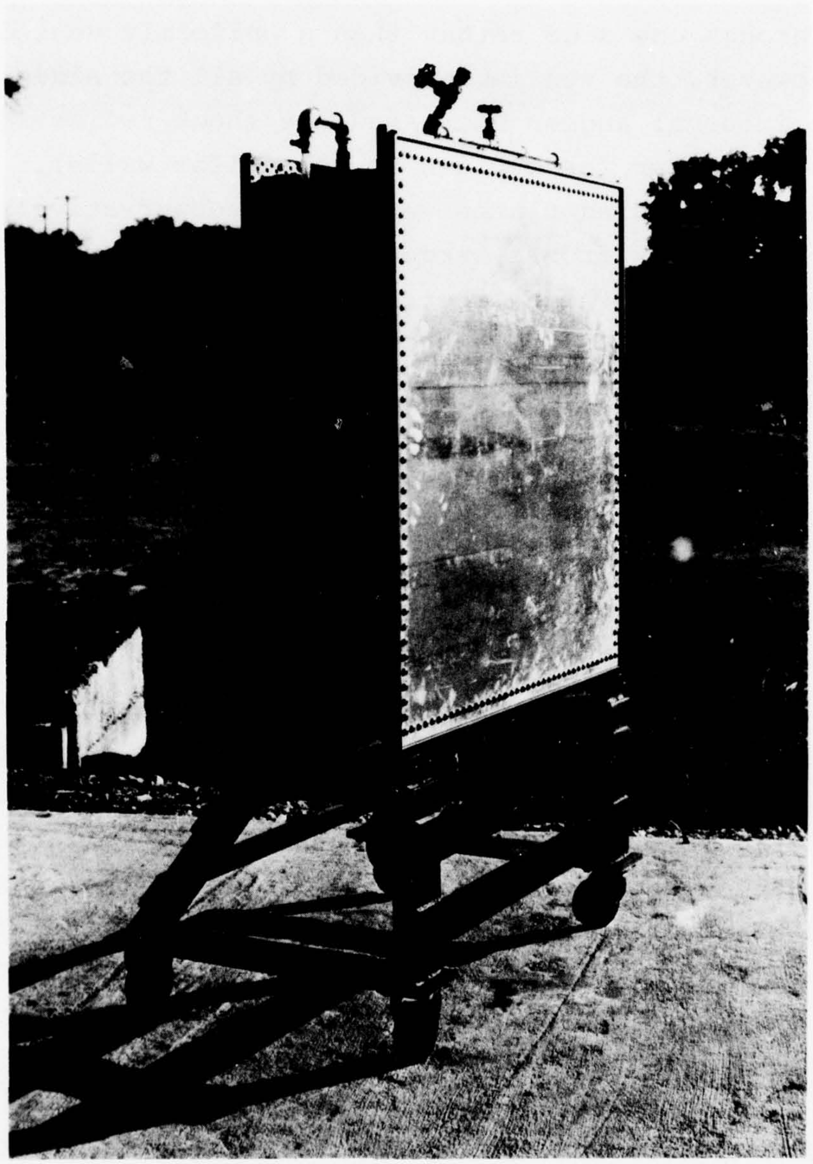


Figure 6. Simulated Aircraft Fuel Tank

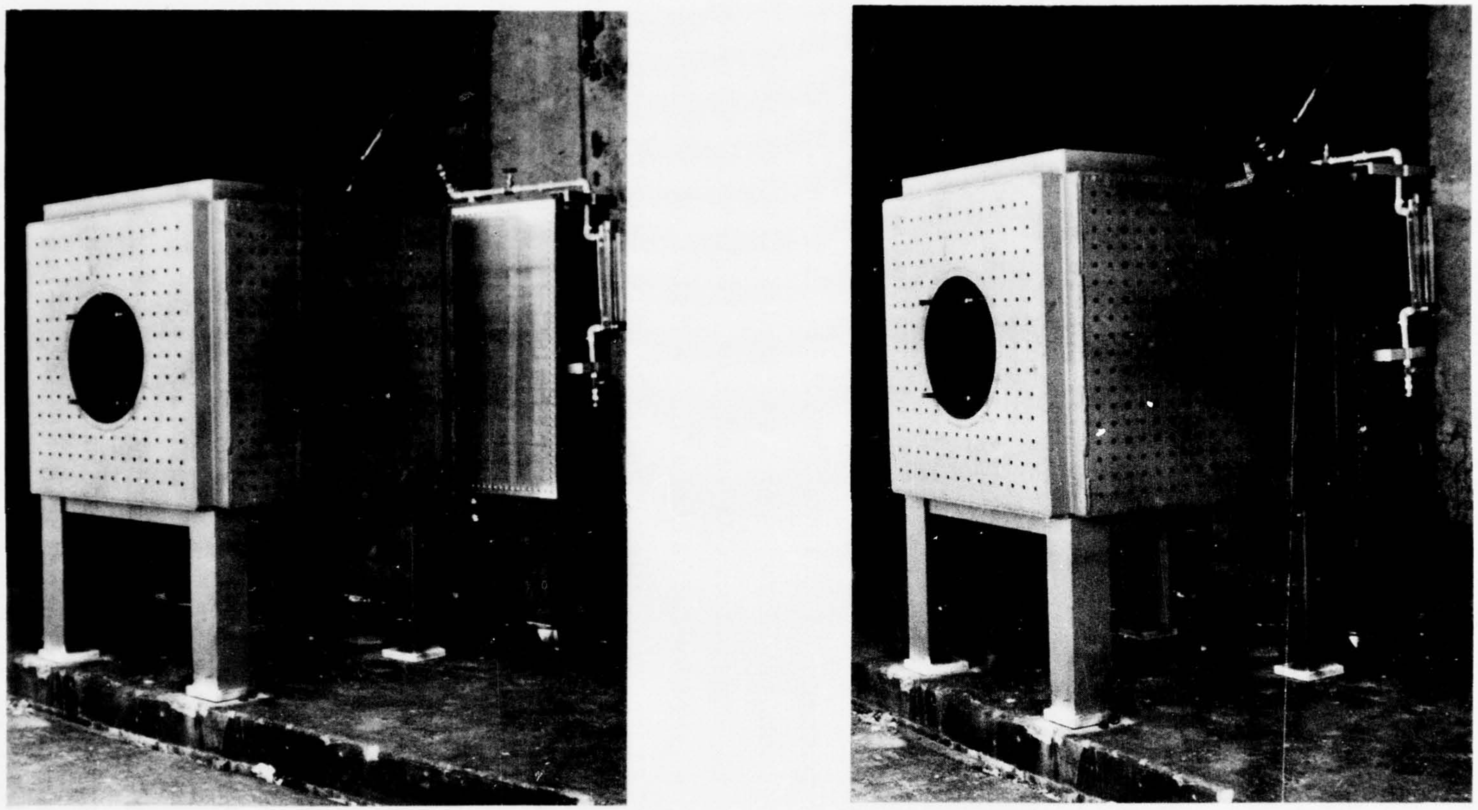


Figure 7. Mating of Target Tank to Blast Simulator

designed to sustain repeated loads and was fabricated from steel plate welded together. However, as the testing began using the combined fragment and blast loads, considerable warping occurred on the steel frame. This made it almost impossible for the next target plate to be bolted without major redrilling of the bolt pattern used. Therefore, considerable stiffness was added by welding additional steel plates around the exterior of the flanges on the fuel tank frames used to mount the target plates.

Four types of aluminum test panels were used on the front location of the target fuel tank. Two were made from 2024-T3 aluminum and differed in thickness, 0.040 and 0.071 inches (1.02 and 1.80 mm). The other two consisted of panels made from 7075-T6 aluminum of similar thicknesses. These front target plates were bolted to the steel frame using a single-row pattern of screws (M551958) and nuts (AN345C-416) set on 1.0 inch (25.4 mm) centers around the periphery of each plate to simulate a riveted type fastening comparable to that of a particular aircraft. A total of 152 holes had to be drilled in each plate using a hole template which matched the hole pattern on the front flange of the fuel tank. Sealing of the front plates on the tank for the water tests was accomplished by spreading a thin layer of vacuum grease around the flange of the tank.

Only on the full tank tests were aluminum plates used on the rear face of the fuel tank. These rear panels were made from 2024-T3 aluminum plate, 0.10 inches thick (2.54 mm). These panels were interiorly lined with a bladder material similar to that used in the fuel cell of an actual aircraft. The rear panel and bladder material were mounted on the fuel tank frame using an alternating double-row pattern of the same type of screws and nuts used with the front panel. This simulated rivet pattern consisted of 244 holes which were drilled on each aluminum panel tested. Sealing of the rear plates was provided by the bladder material.

A fragment catcher box consisting of bundles of fiberboard was located behind the simulated fuel tank. Any fragments penetrating the simulated fuel tank were safety decelerated in the fiberboard which was backed by a steel plate to keep the fragments within the catcher box.

Instrumentation

The instrumentation used in this test program consisted of four pressure measurement channels used in the preliminary experiments, various velocity screen and breakwire systems used throughout the entire project, and a water flowrate meter for measuring the leak rate from the rear panel on the full fuel tank tests. To determine the effect an off-center detonation in the blast simulator had on the pressure loading to the front panel of the fuel tank, pressure measurements were made using a 1-inch (25.4 mm) steel plate on the open side of the blast simulator. This plate had four pressure transducers mounted: one at the center, the second 10 inches (254 mm) down from the center along the vertical centerline, the third 10 inches (254 mm) to one side along the horizontal centerline of the plate, and the fourth completed a square pattern on one quadrant of the plate. Figure 8 shows the four pressure transducers in place. The four transducers were Susquehanna Model ST-2 which have a natural frequency of 250 kHz and a pressure range of 0.1 to 500 psi (0.7 to 3448 kPa). These piezoelectric transducers were connected to PCB Piezotronics, inline source followers Model 402A13, and powered and conditioned by a six channel PCB Model 483A02 unit. The output signal of each conditioned channel was then recorded on magnetic tape using an Ampex FR-1900 tape recorder with Wideband II, FM electronics. The data were recorded at 60 ips (1.52 m/s) with a frequency range of 0 - 250 kHz. The data were played back with a reduction speed ratio of 32 into a Bell & Howell Model 5-164 oscillograph recorder with 1 kHz upper frequency response galvonometers. The resultant playback frequency range was then 0 - 32 kHz.

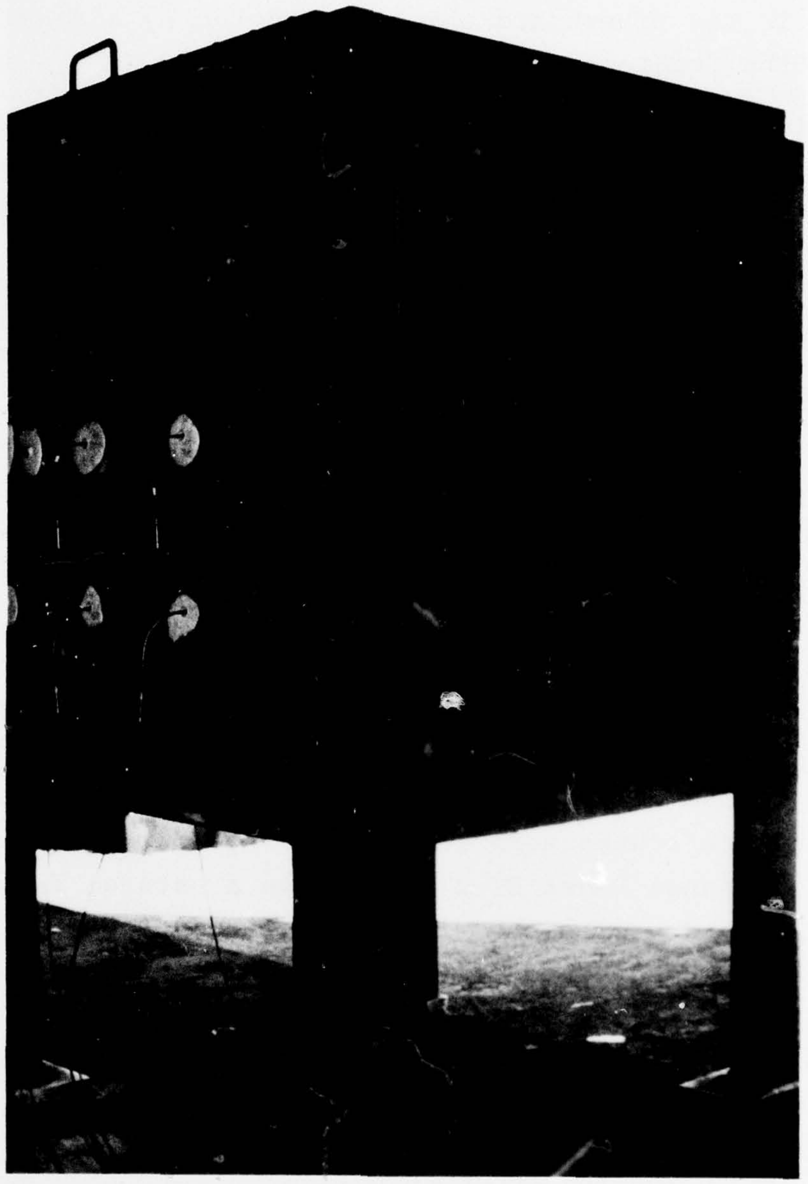


Figure 8. Pressure Transducers Mounted on Steel Plate

Throughout the testing program, several velocity screens, electronic and optical, and breakwires were used to generate electrical pulses for starting and stopping electronic interval counters, Hewlett-Packard Model 5304A with Model 5300A main frames. These time interval measurements were made primarily to determine the fragment average velocity over the distance between the gun muzzle and the front target plate of the fuel tank.

On the full tank tests the water leak rate from the wound in the rear wall was measured after each test using a Dwyer Model RMC-145-BV variable area flowmeter. The front aluminum wall of the fuel tank was removed after each test and replaced with one to be tested subsequently. The fuel tank was refilled with water while temporarily stopping any leakage through the wound on the rear plate. The water in the tank was pressurized with air to 1.15 psig (7.93 kPa) and the inlet water valve adjusted to match the flow out of the wound. The flow measured by the flow meter after the level in the tank was maintained constant was then recorded as the leak rate of the perforated rear aluminum panel.

Data Reduction

The pressure-time data obtained in the preliminary experiments were processed to obtain engineering plots of the pressure and impulse traces. The oscillograph records were reduced by manually digitizing them into a Hewlett-Packard Model 9830 microprocessor system. The BASIC program used to digitize the pressure-time histories also integrated the histories to obtain the specific impulse, properly scaled each parameter, and printed out the peak values. A Model 9862A plotter was used to obtain permanent copies of the data with engineering units for analysis.

All time interval measurements made throughout the program were reduced to average velocities by simply dividing the time increments by the distance over which each one was made.

III. RESULTS AND DISCUSSION

The 87 tests conducted and discussed in this report divided the program into two separate phases. The first phase consisted of 54 preparatory tests which were requisite to bring together the multifragment launching technique developed in Reference 1 and the blast simulator used in Reference 2 to achieve the objective of the program. The second phase of the program was the 33 experiments performed using the simulated fuel tank and loading it with fragments only and with a synchronized fragment and blast load.

The preparatory or preliminary tests of the first phase of the program were conducted using the blast simulator only, the 30 mm gun only, and the combination of the simulator and the gun. None of these experiments used the simulated fuel tank aluminum panels. One or more set of results were obtained from each group of tests which contributed to the generation of the two types of loading used in the fuel tank tests of the second phase of the program. This main set of experiments consisted of loading the simulated fuel tank in two different conditions, empty and full of water. Fragments alone and in combination with a blast load were used against the simulated fuel tank in these tests.

Blast Simulator Tests

Experiments were performed using the blast simulator primarily to determine if an off-center detonation in the chamber (to allow fragment passage) produced a pressure loading similar to a central detonation. In addition, because the blast load was to be synchronized with the fragment load on the combined load tests of the simulated tank, a way of obtaining repeatable charge detonation times was set up and the travel time of the blast wave to the target was determined in these 22 simulator tests.

Because all previous testing with the blast simulator was done with an explosive sheet located on the central vertical plane of the chamber perpendicular to the test panel, testing was necessary to see if the blast loading from an off-center detonation was similar to the central one. Single and double thicknesses of Detasheet® C explosive, 0.04 inches (1.02 mm) thick of equal mass were used in these tests. Figure 9 shows a single sheet in the blast simulator prior to a test. The data from these 22 experiments showed that the pressure time profiles for the off-center detonations were similar to the center detonations. However, it became evident that the double sheet charges produced a greater variation in the data than the single sheet charges. Consequently, most of these experiments used the single sheet explosive.

The 16 tests using a single 7 in x 7 in (178 mm x 178 mm) sheet weighing approximately 0.21 lb (95 gm) produced the pressure and impulse data shown in Table 1. Note that the third column indicates whether the charge was located at zero inches (center), or to left or right off center. Figure 10 is a sketch of the transducer locations on the steel plate used on the target plate side of the blast simulator. The average pressure for all these tests is 52.6 psi (363 kPa), very close to the desired loading pressure of 50 psi (345 kPa). The average specific impulse measured is 168 psi·ms (1158 kPa·ms) and the observed durations were all about 12 ms. In general, the charges located further away from the center produced the largest difference in the measurements from location to location. Therefore, for the combined blast and fragment tests on the fuel tank, an off-center location of 5.5 in (140 mm) was used. This location, also shown in Figure 10, provided enough clearance to keep the fragments from striking the charge. An example of a set of pressure records from an

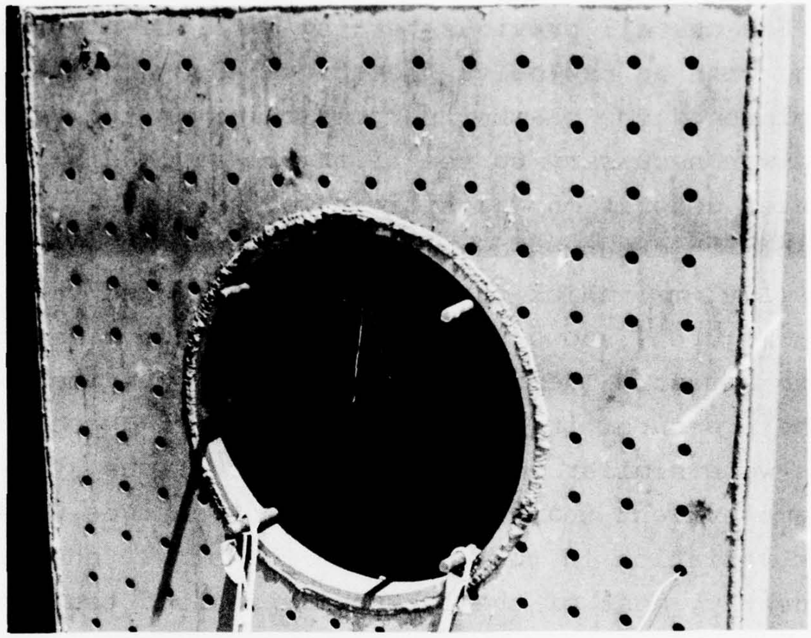


Figure 9. Off-Center Sheet Explosive in Blast Chamber

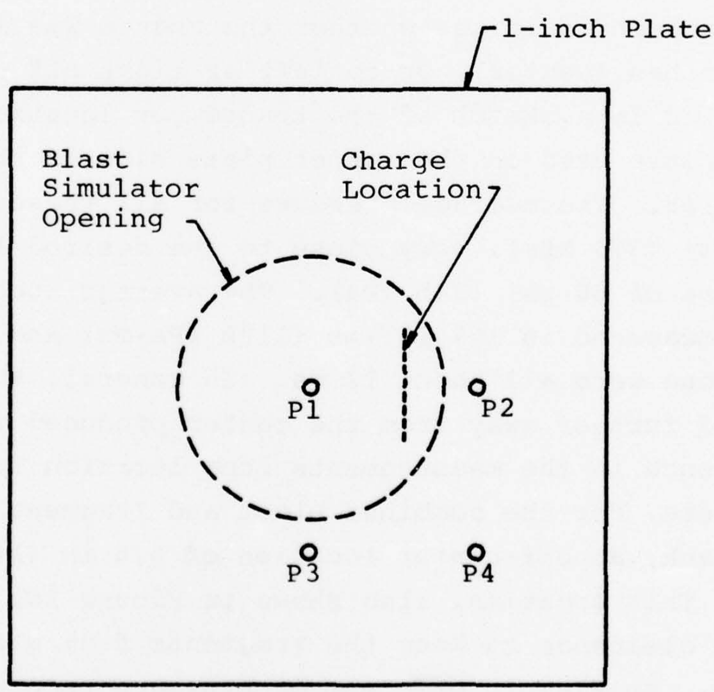
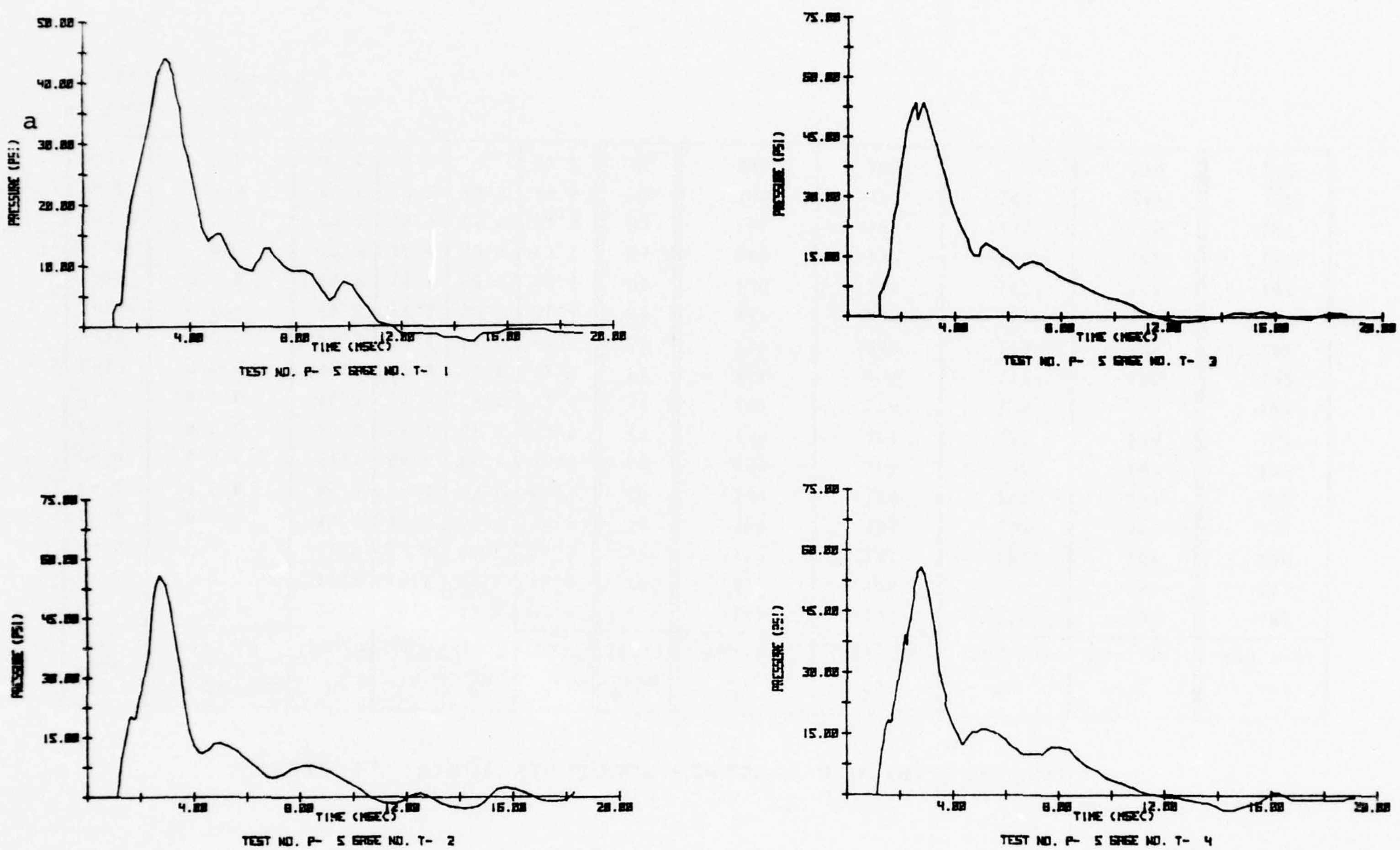


Figure 10. Pressure Transducer Locations

Table 1. Blast Simulator Pressure and Impulse Data

Test No.	Off-Center Location (in.)[a]	P_1 (psi)[b]	P_2 (psi)	P_3 (psi)	P_4 (psi)	P_{ave} (psi)	I_1 (psi·ms)	I_2 (psi·ms)	I_3 (psi·ms)	I_4 (psi·ms)	I_{ave} (psi·ms)
P- 3	0	50.8	48.8	47.1	41.5	47	140	172	176	155	161
P- 4	0	42.4	40.1	51.1	45.8	45	140	136	154	159	147
P- 5	0	43.9	55.8	53.6	55.9	52	153	141	182	164	160
P- 6	9.5 R	42.4	47.0	46.4	48.8	46	139	155	137	179	153
P- 7	9.5 R	45.8	49.4	53.6	51.5	50	148	180	167	191	172
P- 8	9.5 L	54.1	64.6	66.8	68.0	63	157	169	196	167	172
P- 9	9.5 L	36.0	55.7	41.2	45.5	45	139	204	121	178	161
P-10	9.5 L	46.8	58.5	59.4	63.4	57	148	176	185	184	173
P-13	9.5 R	47.0	77.2	57.8	52.6	59	156	239	187	185	192
P-14	9.5 R	45.1	72.4	54.1	47.0	55	167	248	173	176	191
P-15	5.5 R	47.0	77.2	60.7	51.4	59	147	230	181	151	177
P-16	3.5 R	48.9	75.2	64.0	54.4	61	149	234	187	154	181
P-19	0	47.2	37.6	49.9	43.1	44	169	132	185	142	157
P-20	5.5 R	50.9	45.9	59.5	51.3	52	165	141	196	165	167
P-21	5.5 R	55.1	43.1	62.5	49.5	53	156	121	197	149	156
P-22	5.5 L	48.4	55.1	-	49.2	54	146	182	-	179	169

[a] 1 inch = 25.4 mm
[b] 1 psi = 6.895 kPa



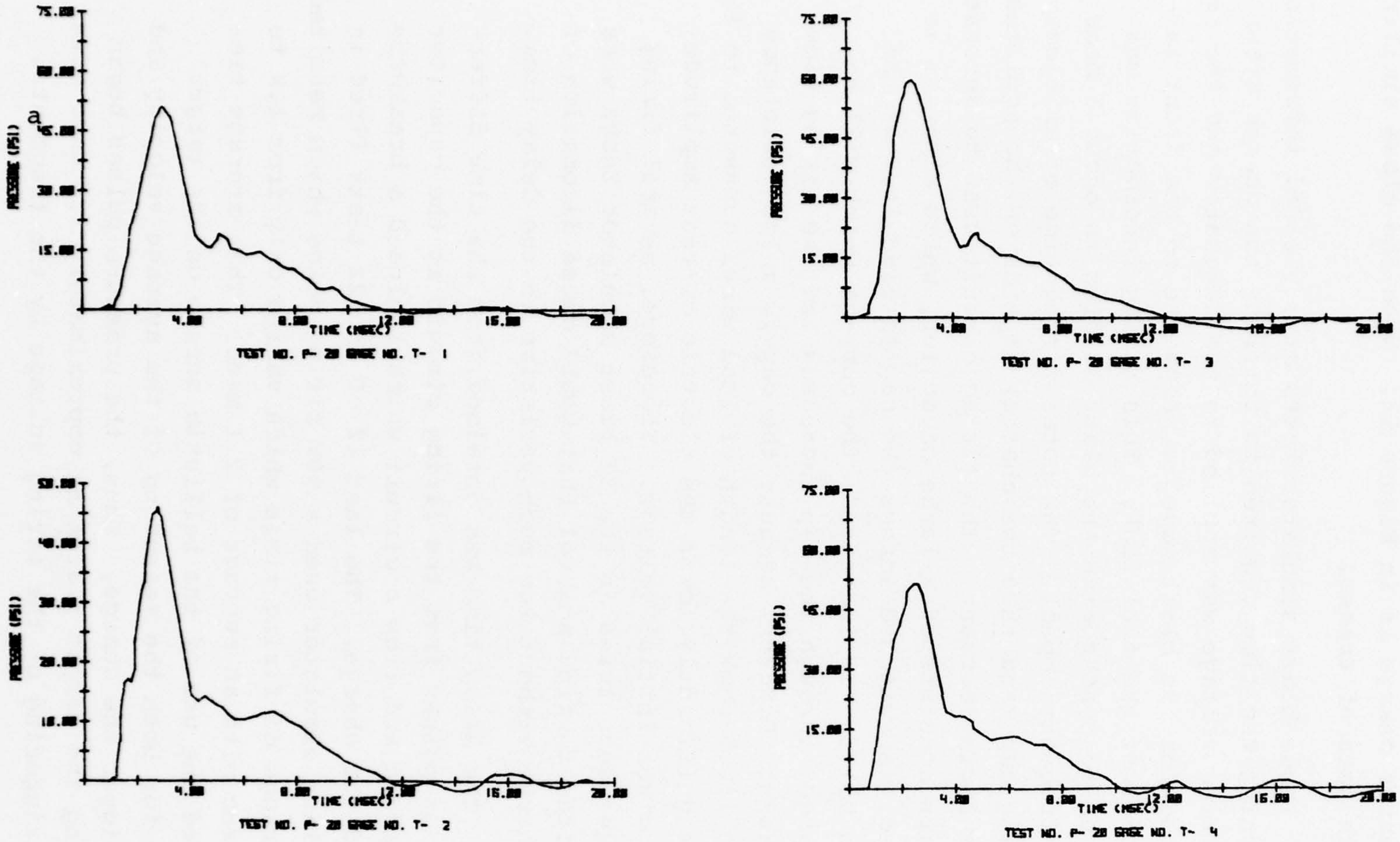
[a] 1 psi = 6.895 kPa

Figure 11. Blast Simulator Pressure Traces with Charge at Center

off-center charge is in Figure 12. Note the close similarity of both sets of traces.

These blast simulator tests also yielded information concerning the time required to initiate the charge after the firing voltage was applied to the detonator and the time required for the blast wave to propagate to the front target panel of the fuel tank. This timing information was required to synchronize the blast loading to occur 3 msec after fragment impact. The total firing time of an electric blasting cap (and thus the charge) depends on the amplitude of the firing current. The firing circuit used to detonate the caps consists of a large capacitor, which after it is charged, is switched across the cap to fire it. As the charge voltage is increased, the current which will be discharged through the cap increases and the firing time decreases. However, because the cap is a low resistance device (<0.5 ohm) the length of lead wires connected to it will significantly lower the electric current amplitude for a given initial voltage. Therefore, several firing voltages were tried as the 22 blast simulator tests were conducted to find a level that would cause detonation of the charge without too much variation in the delay time.

The delay time was obtained from the time differences of pulses from the firing circuit as the capacitor discharged and from a circuit which included a breakwire around the charge. The last 12 of the 22 tests fired in the blast simulator used a 90V firing pulse which resulted in a range of firing times which varied only from 1.8 to 2.7 msec with an average of 2.1 msec. This average time allowed the use of the ballistic screen on the target plate for both the measuring of the average velocity and to trigger the charge. Thus, the pressure pulses began loading the target plates at approximately 2.1 msec after the triggering of the firing voltage by the fragments.



[a] 1 psi = 6.895 kPa

Figure 12. Blast Simulator Pressure Traces with Charge Off-Center

Because the blast loading took about 2 msec to reach maximum pressure (see Figures 11 and 12), the blast pressure rise to peak loaded the plate approximately from 2.1 to 4.1 msec after fragment impact, adequately close to the 3 msec delay sought.

Gun Tests

A total of 32 firings were conducted with the 30 mm gun in preparation for the simulated fuel tank tests. These firings included 19 to position and aim the 30 mm gun, to obtain the desired fragment spread, to position the sabot stripper plate, and to bracket the propellant load needed to project the five fragments with an average velocity of 4500 fps (1,372 m/s) over the range of 30 ft (9.14 m).

Eight of the 30 mm gun tests were fired for the purpose of establishing that a load of 1475 gr (95.58 gm) propelled the fragments with the average velocity desired and to establish an average velocity reference for comparing the effects on the fragment velocity of the 8-inch (203 mm) thick reticulated foam used in the blast simulator. Two other firings were also made with the same propellant load to obtain velocity data and check the operation of the fragment and blast synchronizing circuit.

The fragment average velocity was determined by measuring the flight time over the 30 ft (9.14 m) range using a breakwire at the barrel exit and a foil ballistic screen mounted on the fragment catcher and positioned where the target panels would eventually be located. Table 2 shows the average velocities measured on the ten gun tests. The average of these ten velocities is 4512 fps (1375 m/s) with very little scatter. Thus, after these tests a high level of confidence was established for having the proper propellant load to achieve the desired average velocity.

Table 2. Average Fragment Velocities

Test No.	Velocity (fps)[a]
G-20	4617
G-21	4472
G-22	4502
G-23	4462
G-26	4605
G-27	4495
G-28	4300
G-29	4680
G-31	4487
G-32	4501

To determine if any difference in the average velocity could be detected when the fragment penetrated the foam in the blast chamber, three tests were fired through foam suspended at the target location just in front of the velocity screen. The results are shown in Table 3. These values are well within the scatter of those measured without foam. As an additional measure of the foam effect, an average velocity over the last 5 ft (1.52 m) of the trajectory, which included the foam location, was measured on some tests and compared to the 30 ft

Table 3. Average Fragment Velocities through Foam

Test No.	Velocity (fps)[a]
G-24	4488
G-25	4533
G-30	4412

[a] 1 fps = 0.305 m/s

(9.14 m) average velocities. Because the foam would have more effect on the average velocity over the shorter trajectory, the difference between the average velocities would show more of a difference than just the air drag effects for the tests without the foam. The results are tabulated in Table 4. These results indicate that the effect of the foam on the velocities of the fragments is insignificant. Therefore, no adjustments were required on the propellant load for all tests in which the blast simulator was used.

Table 4. Velocity Differences With and Without Foam

Test No.	Foam	30-ft Velocity (fps)[a]	5-ft Velocity (fps)	Difference (fps)
G-26	No	4605	4492	113
G-27	No	4495	4398	97
G-28	No	4300	4202	98
G-29	No	4680	4566	114
G-24	Yes	4488	4359	129
G-25	Yes	4533	4425	108
G-30	Yes	4412	4325	87

[a] 1 fps = 0.3048 m/s

The last two gun firings were also used to check the firing circuit for synchronizing the fragments and the blast. A small charge was fired along with the fragments and the detonation time measured and compared to those measured in the blast simulator tests. Fragment velocity and delay time measured were as expected. In all the fuel tank tests, both the average fragment velocity and the charge firing delay time were monitored to insure each target plate was being loaded as specified for each test.

Empty Fuel Tank Tests

As originally planned, 16 tests were conducted with

the simulated fuel tank empty. For these tests, only the front wall of the tank was required. In eight of the tests, the only load on the aluminum panels was to have been the five high-velocity fragments. In the other eight tests, a combined load of five fragments and a nominal 50 psi (345 kPa) blast pressure pulse were to impact the test panels. However, on one of the combined load tests the charge did not detonate due to a fragment severing the target velocity screen cable. Thus, nine tests used fragments only and seven used the combined load. The front test panels were fabricated from two types of aluminums, 2024-T3 and 7075-T6. Two different thicknesses were used, 0.040 and 0.071 inches (1.02 and 1.80 mm). The data obtained in each of these empty tank experiments consisted of the average fragment velocity before impact, and photographs of the damaged panels to qualitatively determine the contribution of the blast loading to panel damage.

The nine experiments using the fragments only are listed in Table 5 along with average velocities measured. Note that the average velocities measured in these nine

Table 5. Empty Fuel Tank Tests, Fragment Load

Test No.	Target Material	Thickness (in)[a]	Average Velocity (fps)[b]
1	2024-T3	0.040	4,609
2	2024-T3	0.040	4,601
3	2024-T3	0.071	4,601
4	2024-T3	0.071	4,589
5	7075-T6	0.040	4,499
6	7075-T6	0.040	4,481
30	7075-T6	0.040	4,354
7	7075-T6	0.071	4,520
8	7075-T6	0.071	4,556

[a] 1 in = 25.4 mm

[b] 1 fps = 0.3048 m/s

tests are within essentially the same range as those measured on the preparatory tests using the gun only and averaged 4534 fps (1382 m/s). These nine experiments provided the baseline damage level due to fragments only for the four types of panels used. Damage to these targets was essentially the same, consisting of the multiple holes left by the fragment penetration. No permanent wall deformations could be observed and, consequently, no side view photographs of these target plates were taken. Figure 13 shows two examples of the similar damage inflicted to the nine aluminum panels tested. As can be observed, in most cases the fragment holes on these plates were within circles 5 to 7 inches (127 to 178 mm) in diameter. Also, except for Tests 2 and 5, each fragment penetrated the plates individually. In test 30, a piece of sabot got past the sabot stripper plate and also penetrated the target plate. For this particular test, the additional unintentional fragment was of no consequence to the results. This was the only fuel tank test in which a piece of the sabot traveled beyond the sabot stripper plate.

The seven tests in which the combined fragments and blast loads were used against the front target panels are listed in Table 6 along with the average velocities measured for each test. Note again that the velocities continued to be quite close to the one desired for the entire program. The average value for these tests was 4470 fps (1363 m/s). One velocity was not obtained due to chronograph malfunction. For easier comparison these tests are listed in a corresponding order to the ones using only fragments. As previously mentioned, Test No. 30 was originally designed to use a combined load but because of a cable failure became a fragments only test. This test was not repeated because the damage to the thinner 7075-T6 plate in the similar Test No. 29 was catastrophic. Thus, it was obvious that blast inflicted considerable damage to this particular configuration.

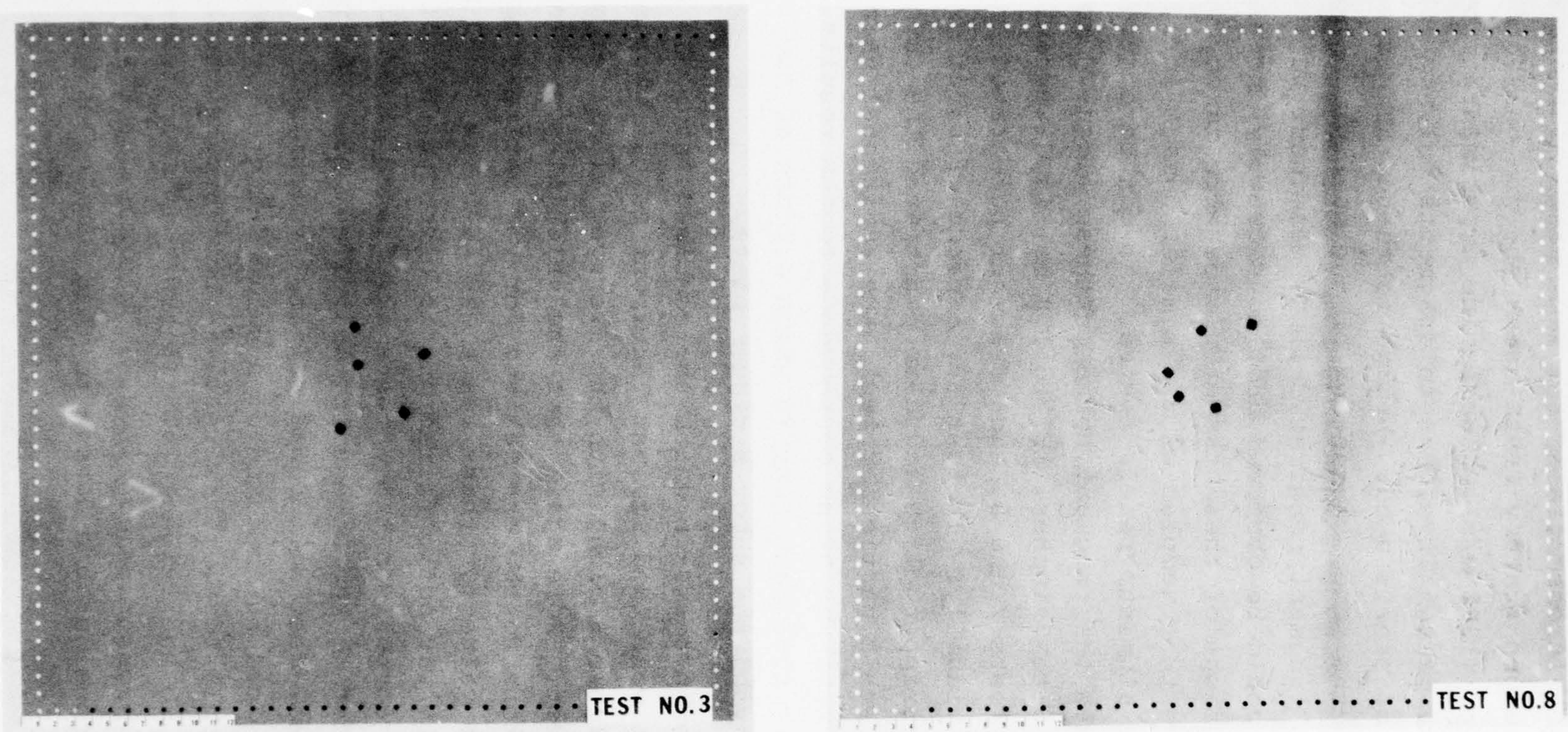


Figure 13. Examples of Fragment Damage to Aluminum Panels Tested with Empty Fuel Tank

Table 6. Empty Fuel Tank Tests, Combined Loads

Test No.	Front Wall Material	Thickness (in)[a]	Fragment Velocity (fps)[b]
9	2024-T3	0.040	4315
27	2024-T3	0.040	4148
10	2024-T3	0.071	4695
28	2024-T3	0.071	4665
29	7075-T6	0.040	--
31	7075-T6	0.071	4408
32	7075-T6	0.071	4594

[a] 1 in = 25.4 mm

[b] 1 fps = 0.3048 m/s

The results of the combined loads tests using an empty simulated fuel tank are shown in Figures 14-17. Both plane and side views for each target plate are shown because of the extensive damage inflicted on most of these aluminum panels. Comparing these photographs with the corresponding ones in the fragments only tests, it is quite obvious that the addition of a blast pressure produces considerably more damage than when the empty tank target plate is hit by only the five fragments.

The damage is much more severe on the thinner panels, as would be expected. Also, for the same panel thickness, the resistance to crack propagation, panel rip-out and fastener failure was greater for the more ductile 2024-T3 aluminum. Gross structural failure was resisted only by the thicker 2024-T3 panels. However, even these two targets sustained some cracking and were permanently deformed 2-3 inches (51-76 mm).

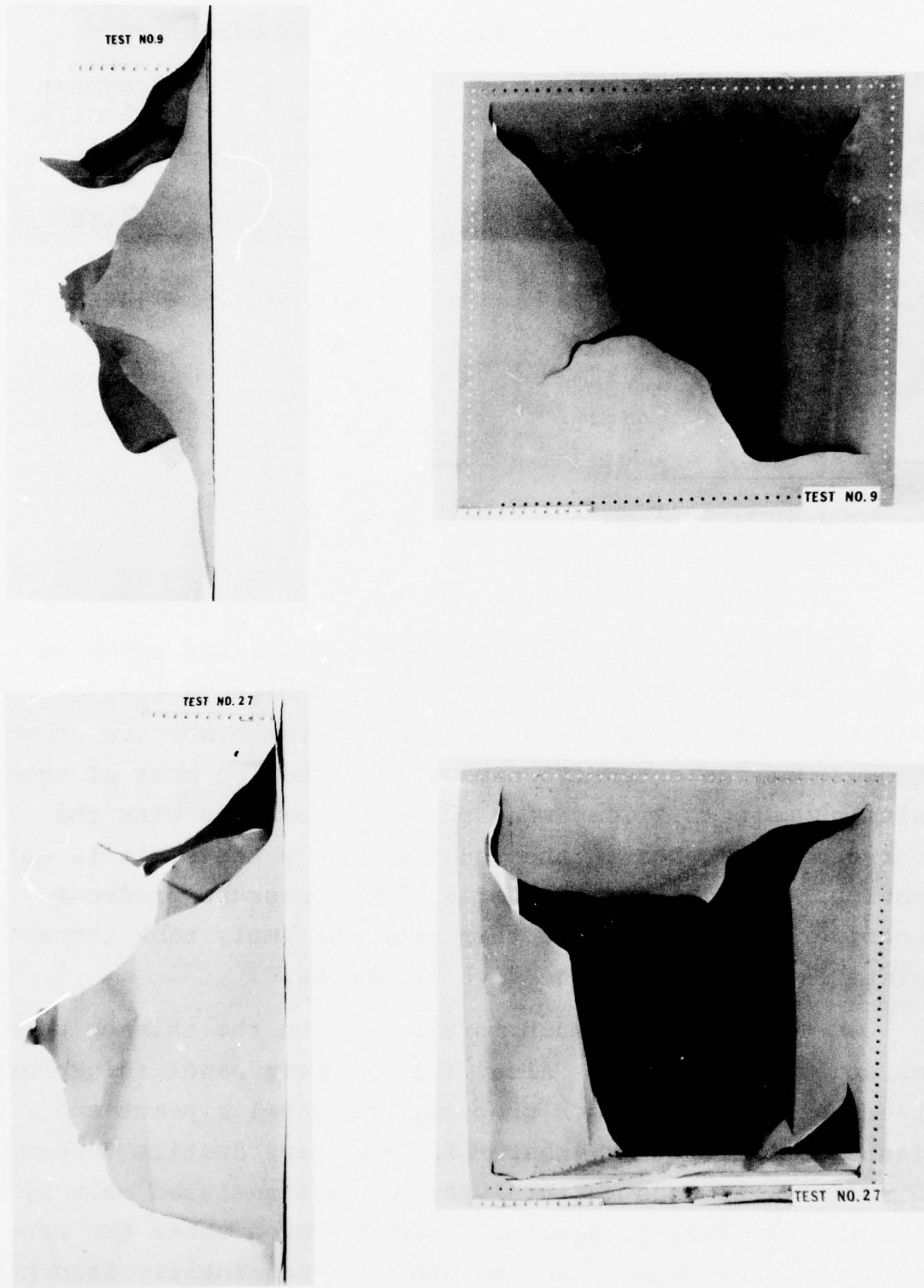


Figure 14. Combined Fragment and Blast Damage to Thinner 2024-T3 Aluminum Front Panels Tested with Empty Fuel Tank

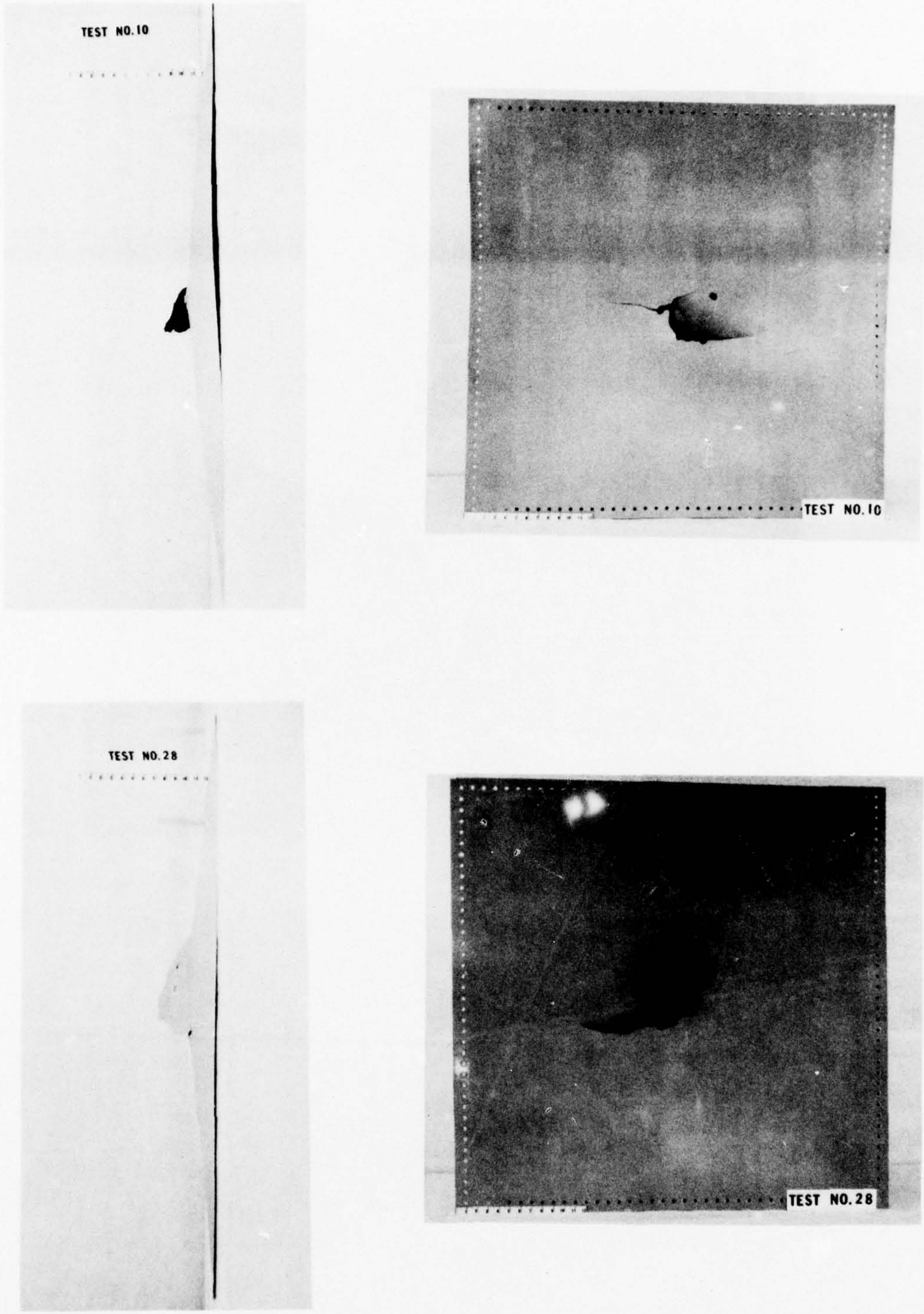


Figure 15. Combined Fragment and Blast Damage to Thicker 2024-T3 Aluminum Front Panels Tested with Empty Fuel Tank

Figure 16. Combined Fragment and Blast Damage to Thinner 7075-T6 Aluminum Front Panel Tested with Empty Fuel Tank

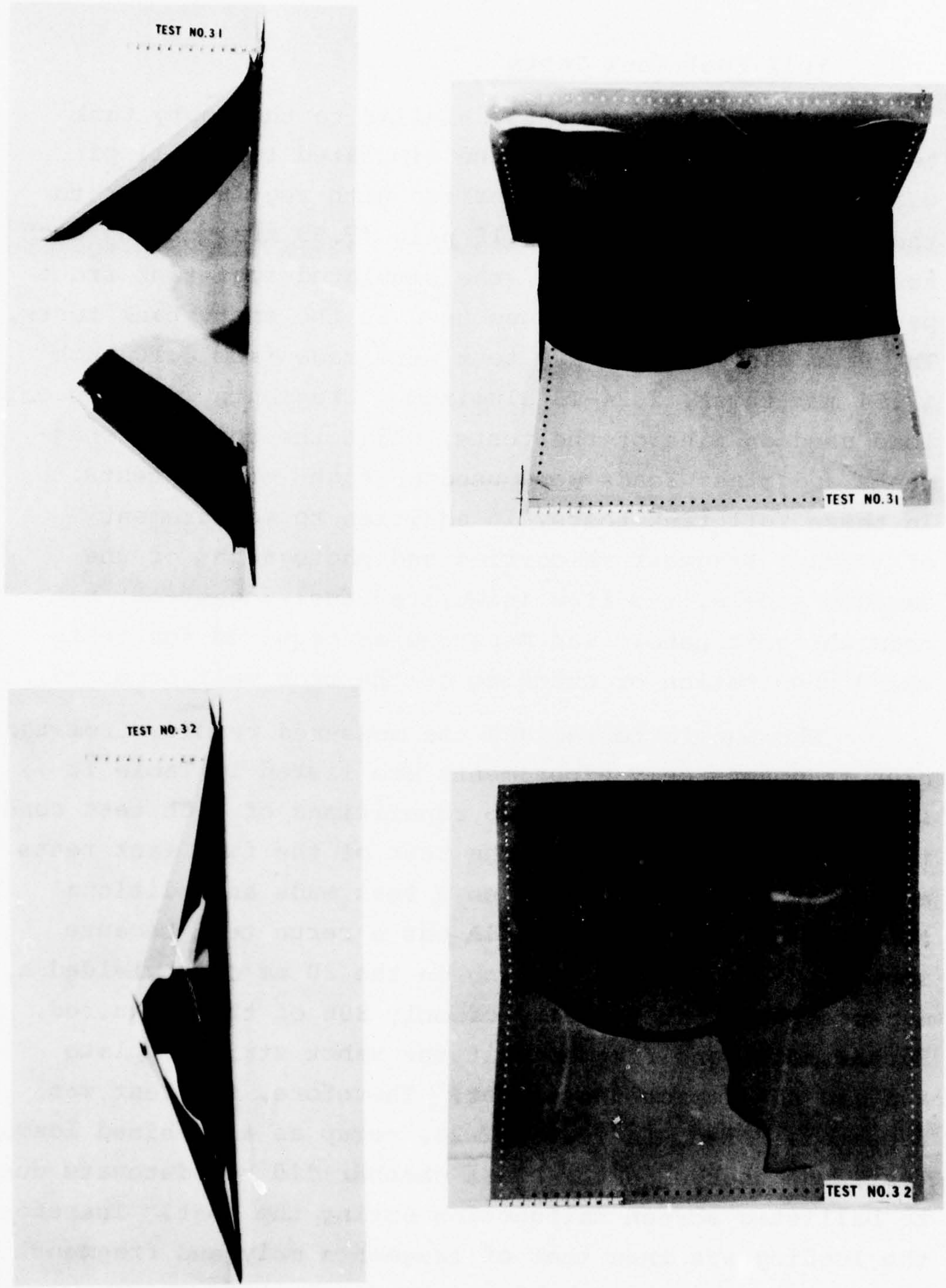


Figure 17. Combined Fragment and Blast Damage to Thicker 7075-T6 Aluminum Front Panels with Empty Fuel Tank

Full Fuel Tank Tests

A set of experiments, similar to the empty tank tests, was conducted with the simulated tank full of water. The water was pressurized with regulated air to the required pressure of 1.15 psig (7.93 kPa) during each test. For these 17 tests, the simulated fuel tank front panels were similar to those used in the empty tank tests. The rear panels for every test were made from 0.10 inch (2.54 mm) thick, 2024-T3 aluminum. Fragments were the only load used on nine of the tests, while the combined fragments and blast loads were used on eight of the tests. In these full tank tests, in addition to measurement of average fragment velocities and photographs of the damaged panels, the flow (simulated fuel ingestion) rate from the exit panels was measured as required for tests where penetration or cracking of the rear wall occurred.

The panels tested and the measured results from the nine fragments only experiments are listed in Table 7. In this series of tests, two repetitions of each test condition were conducted as in the rest of the fuel tank tests except where a malfunction on a test made an additional test necessary. Test No. 11A was a rerun test because incomplete propellant burning in the 30 mm case yielded a measured fragment velocity of only 80% of that required. Furthermore, one fragment hit the sabot stripper plate and did not impact the target. Therefore, the test was repeated. Also, in Test No. 26, setup as a combined loads test, the charge in the blast chamber did not detonate due to ballistic screen malfunction during the test. Therefore, the loading was then that of fragments only and fragment velocity measurement could not be determined.

The average velocities measured were again within the range desired, averaging 4519 fps (1378 m/s). Figures 18-26 are the damage photographs for the full tank tests

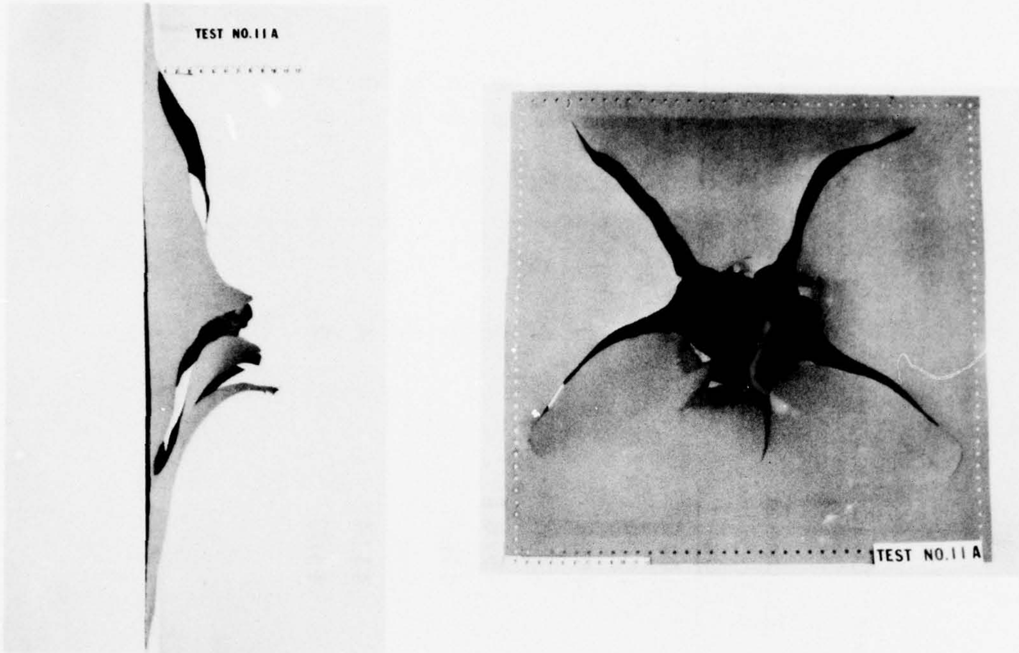
Table 7. Full Fuel Tank Tests, Fragment Load Only

Test No.	Front Panel Material	Panel Thickness (in)[a]	Rear Panel Material	Panel Thickness (in)	Fragment Velocity (fps)[b]	No. Frags. Penetrating Rear Wall	Rear Wall Flow Rate (gpm)[c]
11A	2024-T3	0.040	2024-T3	0.100	4446	4	9.5
12	2024-T3	0.040	2024-T3	0.100	4508	3	8.8
13	2024-T3	0.071	2024-T3	0.100	4688	0	<0.5
14	2024-T3	0.071	2024-T3	0.100	4490	1	2.4
15	7075-T6	0.040	2024-T3	0.100	4578	2	6.6
16	7075-T6	0.040	2024-T3	0.100	4463	5	8.5
26	7075-T6	0.040	2024-T3	0.100	--	2	3.8
17	7075-T6	0.071	2024-T3	0.100	4414	4	7.0
18	7075-T6	0.071	2024-T3	0.100	4562	2	10.0

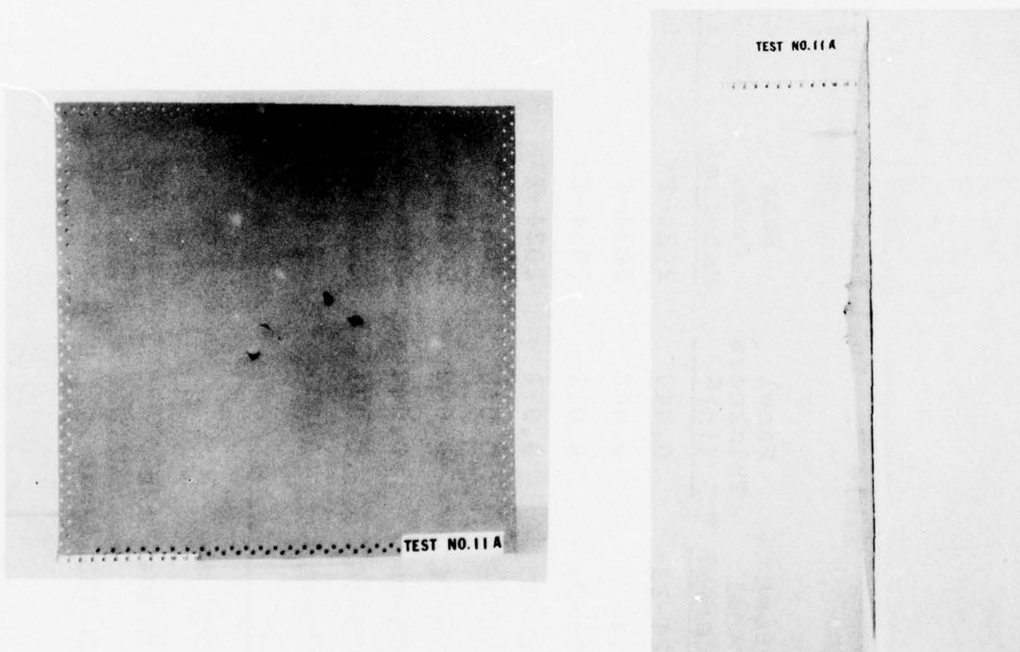
[a] 1 in = 25.4 mm

[b] 1 fps = 0.3048 m/s

[c] 1 gpm = 3.785 ℓ/min

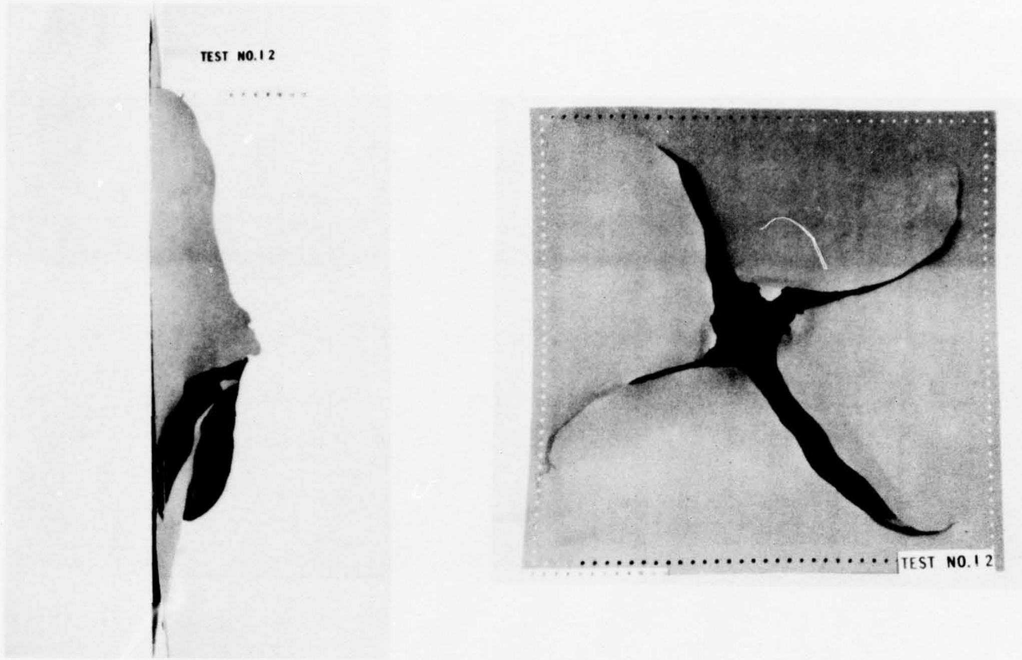


Thinner 2024-T3 Front Panel

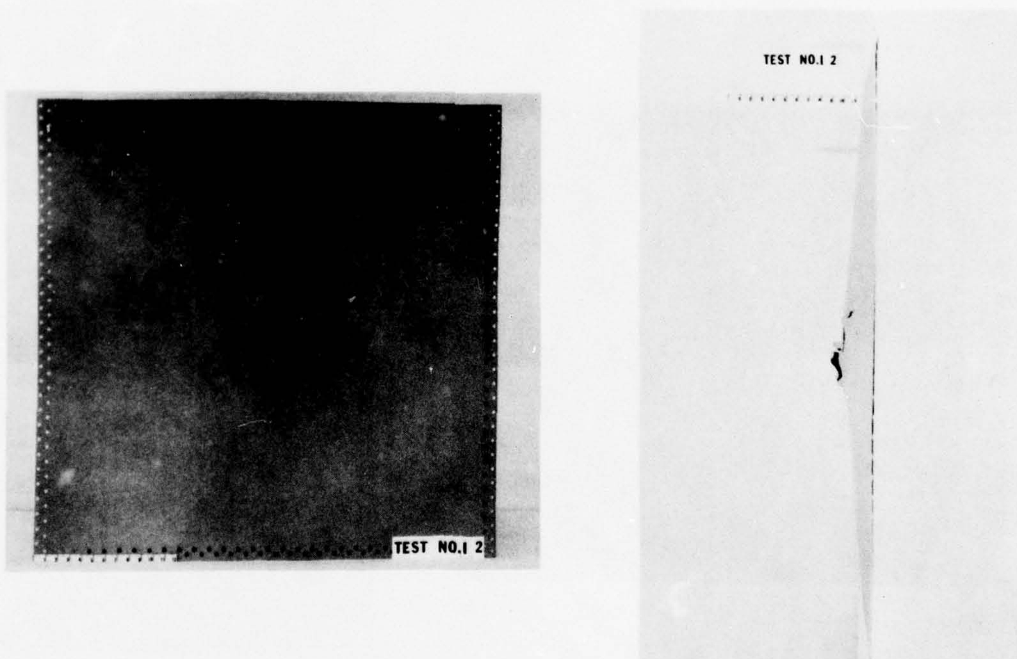


2024-T3 Rear Panel

Figure 18. Fragment Damage to Full Fuel Tank Panels, Test 11A

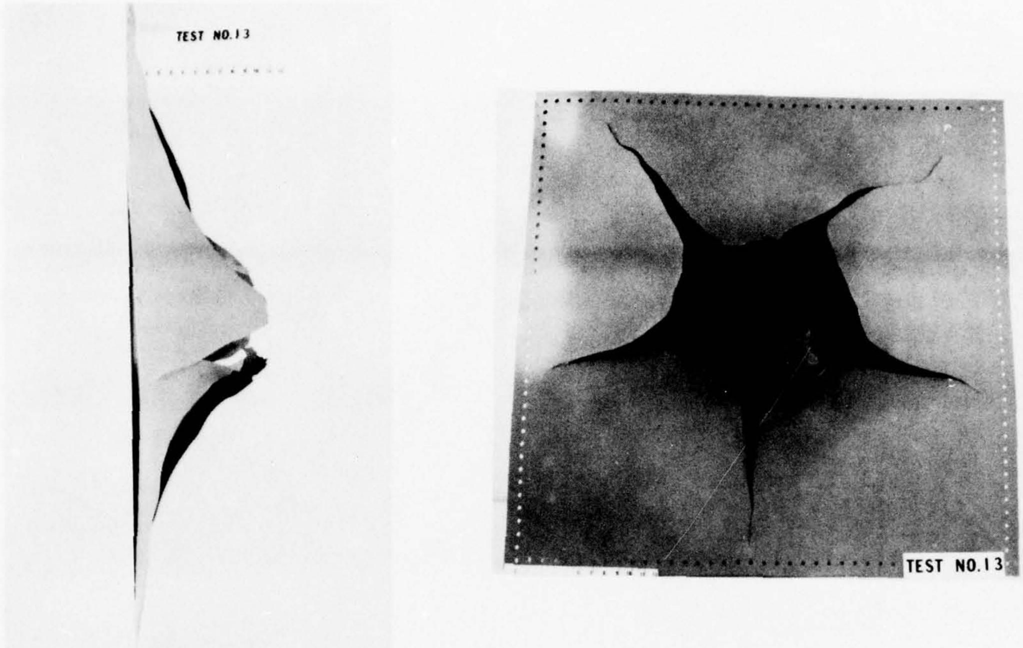


Thinner 2024-T3 Front Panel

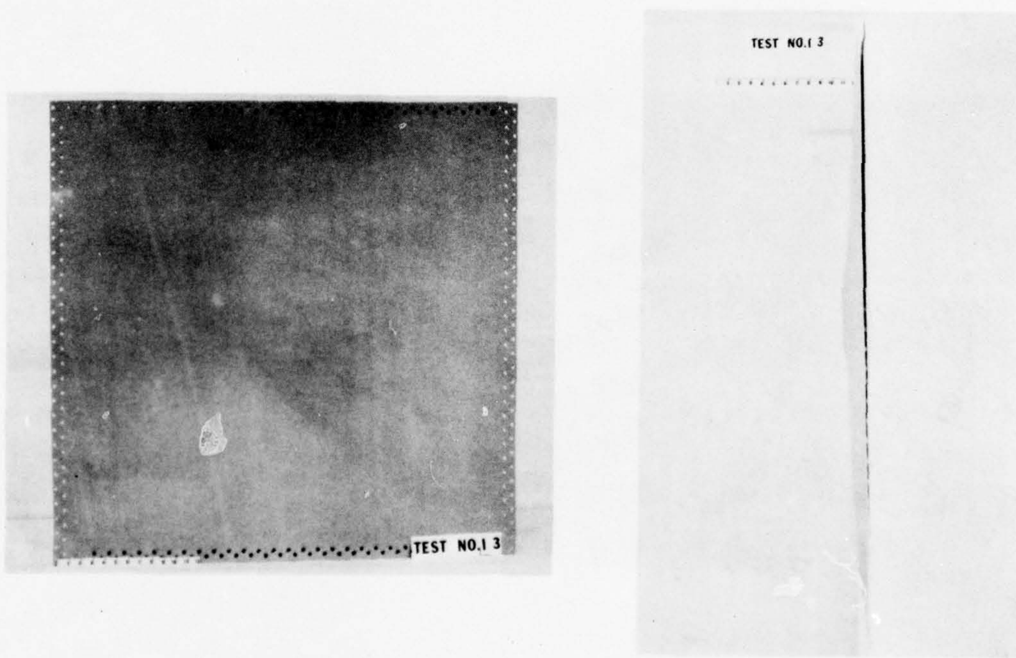


2024-T3 Rear Panel

Figure 19. Fragment Damage to Full Fuel Tank Panels, Test 12

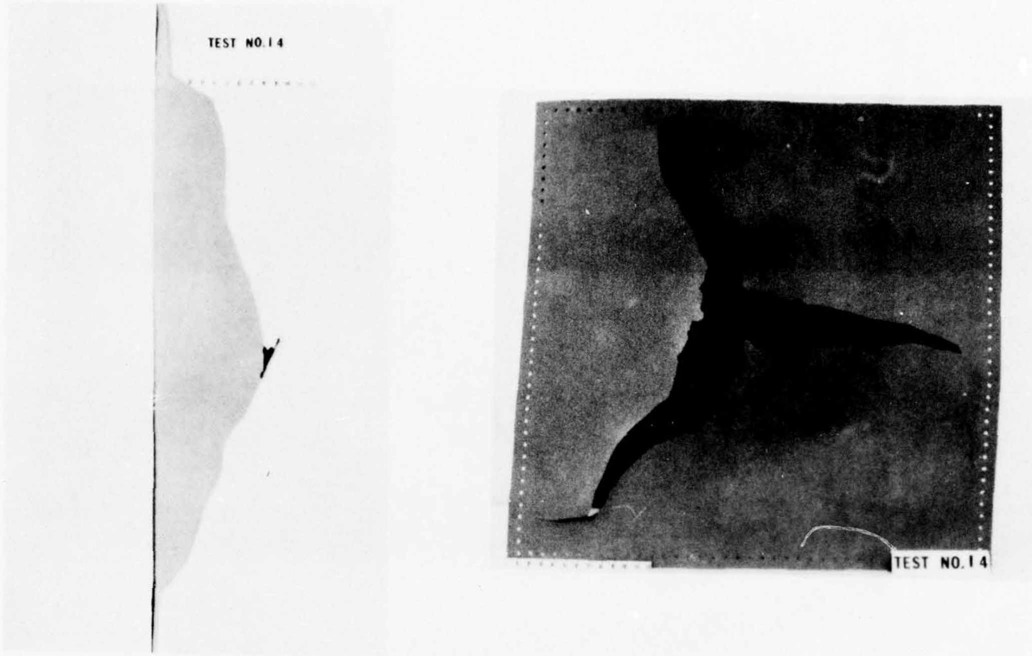


Thicker 2024-T3 Front Panel

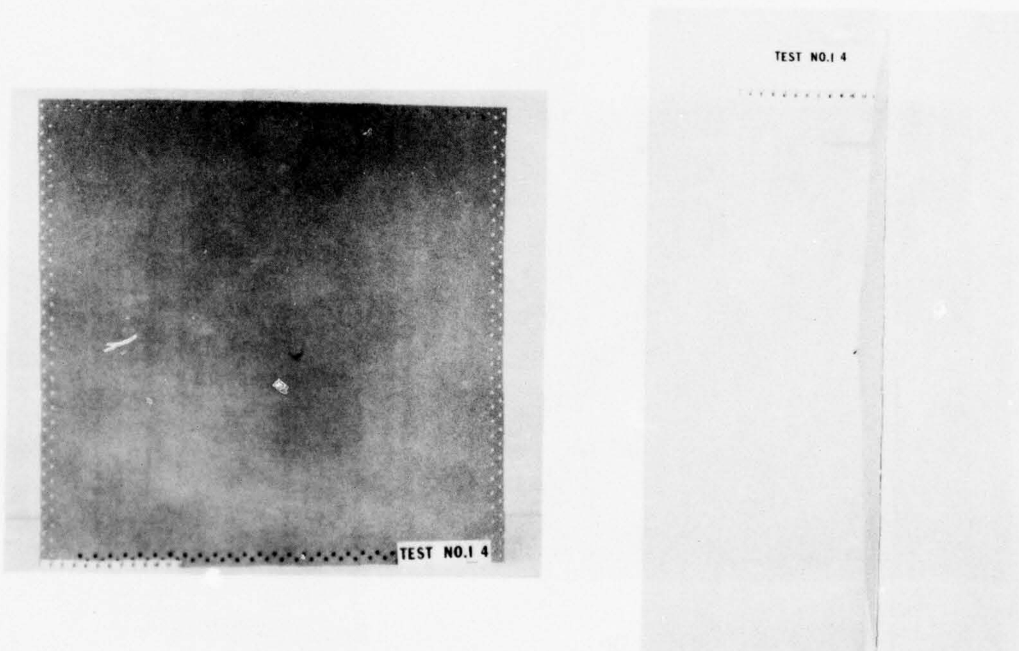


2024-T3 Rear Panel

Figure 20. Fragment Damage to Full Fuel Tank Panels, Test 13

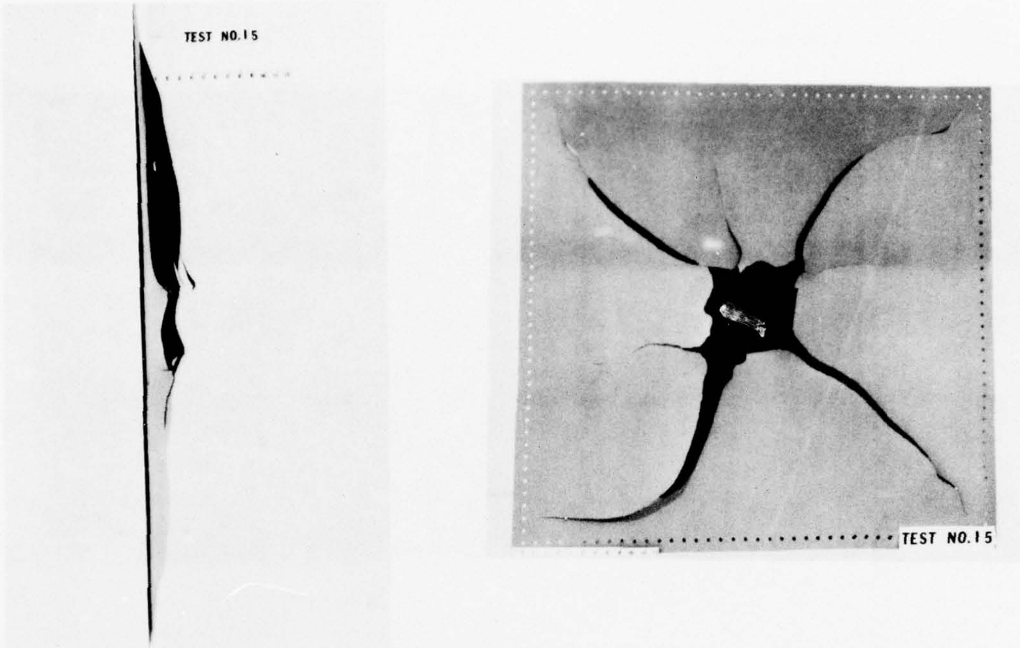


Thicker 2024-T3 Front Panel

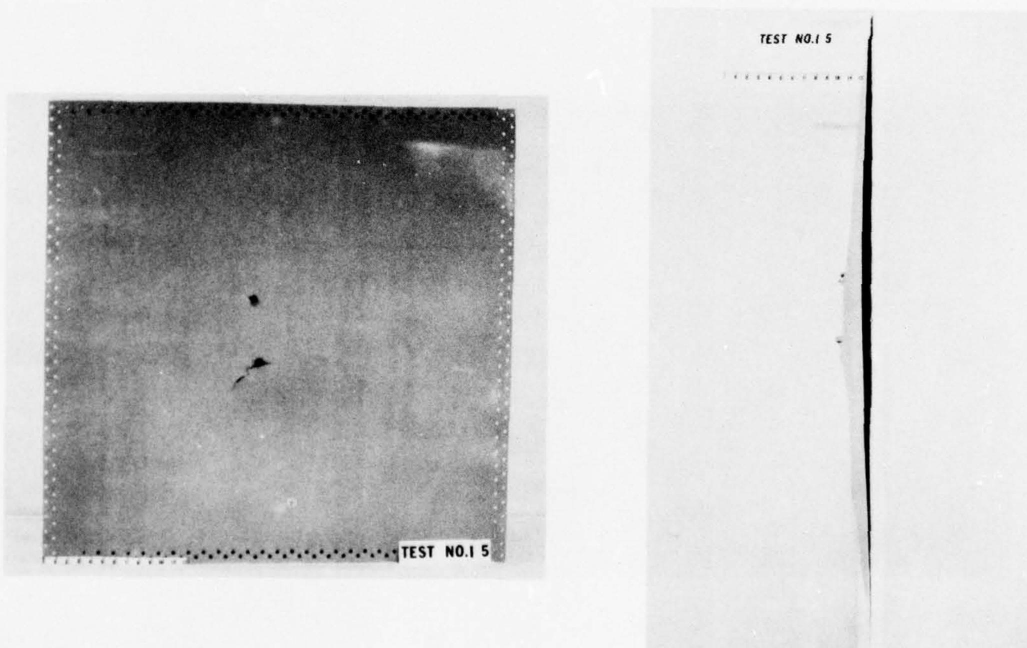


2024-T3 Rear Panel

Figure 21. Fragment Damage to Full Fuel Tank Panels, Test 14

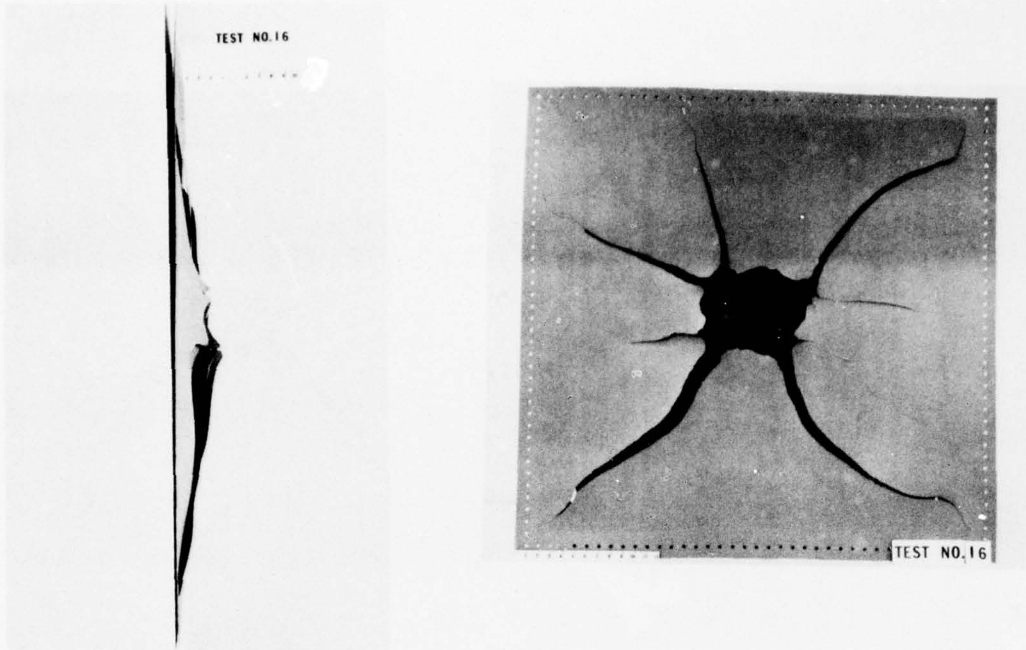


Thinner 7075-T6 Front Panel

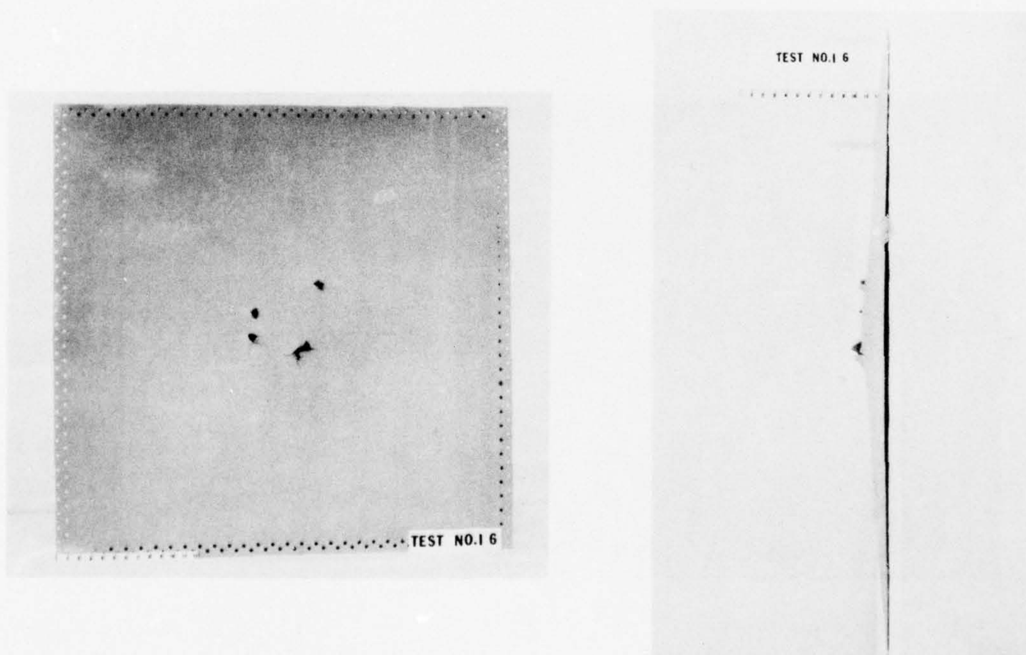


2024-T3 Rear Panel

Figure 22. Fragment Damage to Full Fuel Tank Panels, Test 15

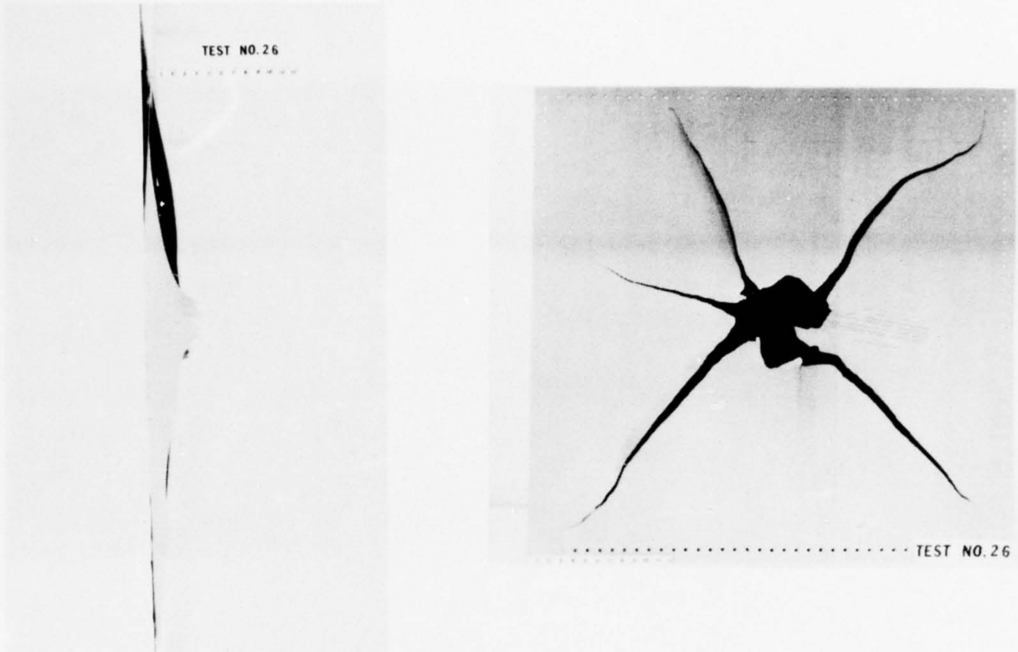


Thinner 7075-T6 Front Panel

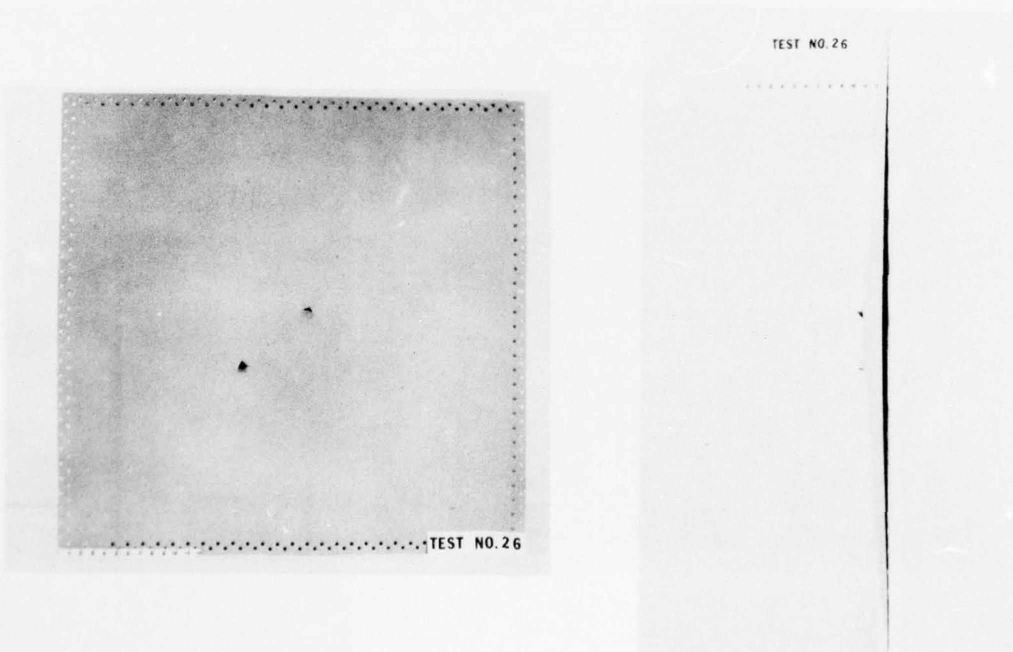


2024-T3 Rear Panel

Figure 23. Fragment Damage to Full Fuel Tank Panels, Test 16

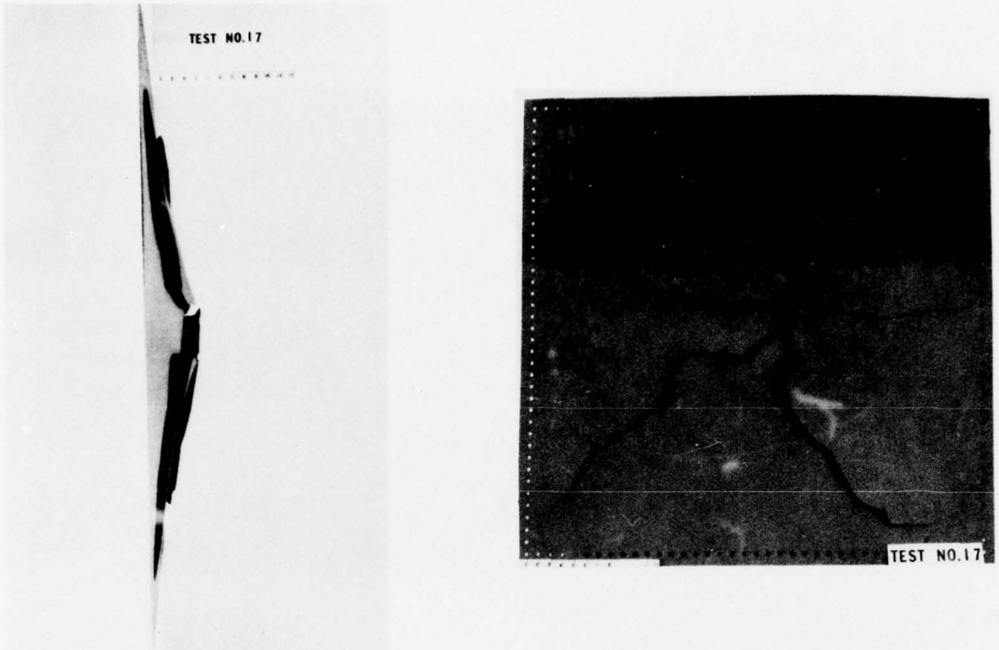


Thinner 7075-T6 Front Panel

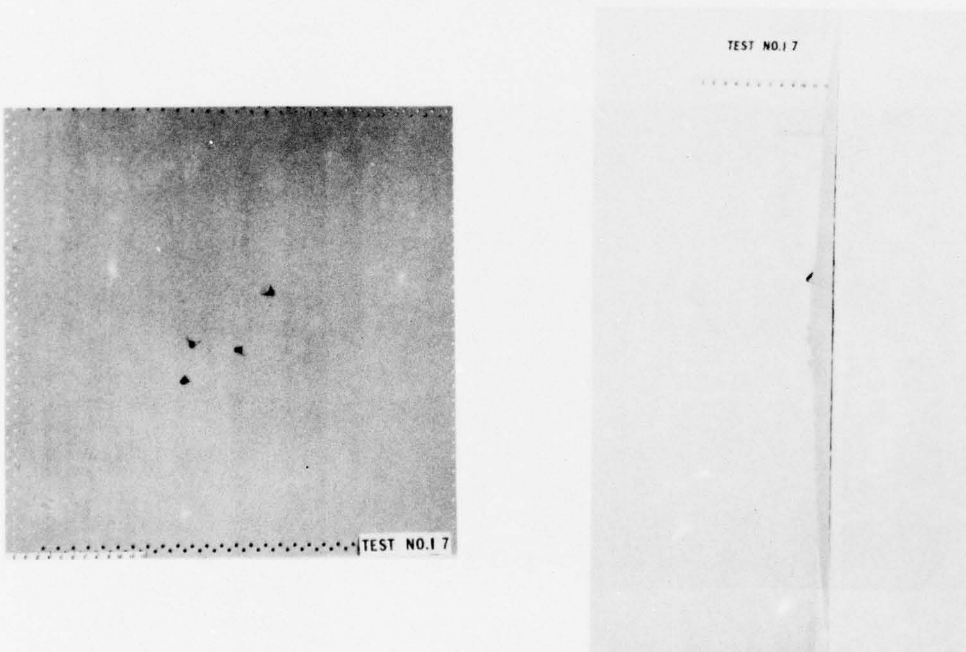


2024-T3 Rear Panel

Figure 24. Fragment Damage to Full Fuel Tank Panels, Test 26

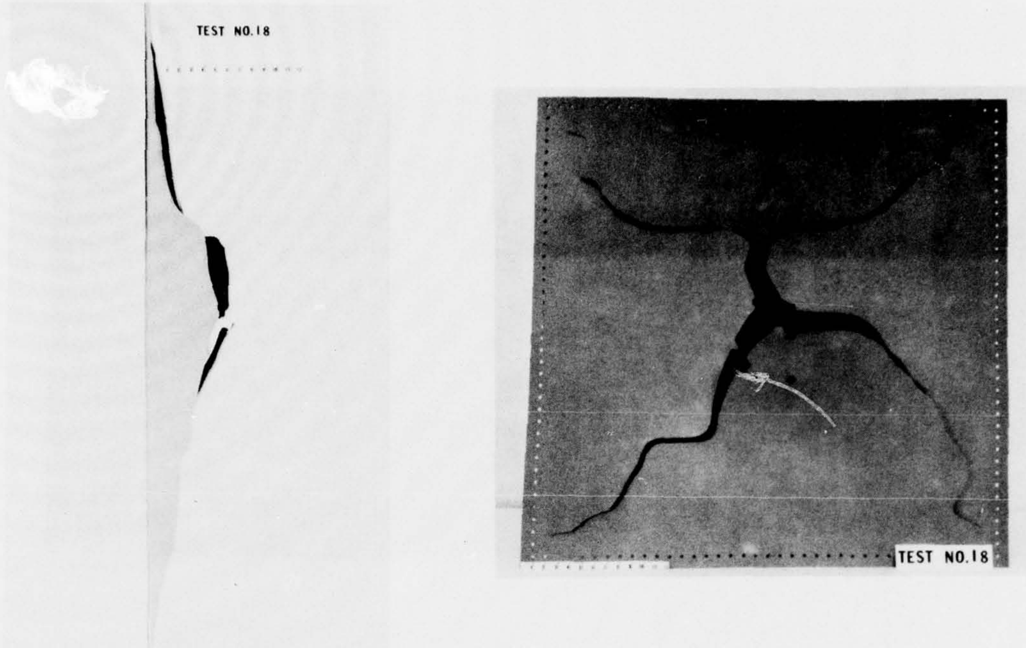


Thicker 7075-T6 Front Panel

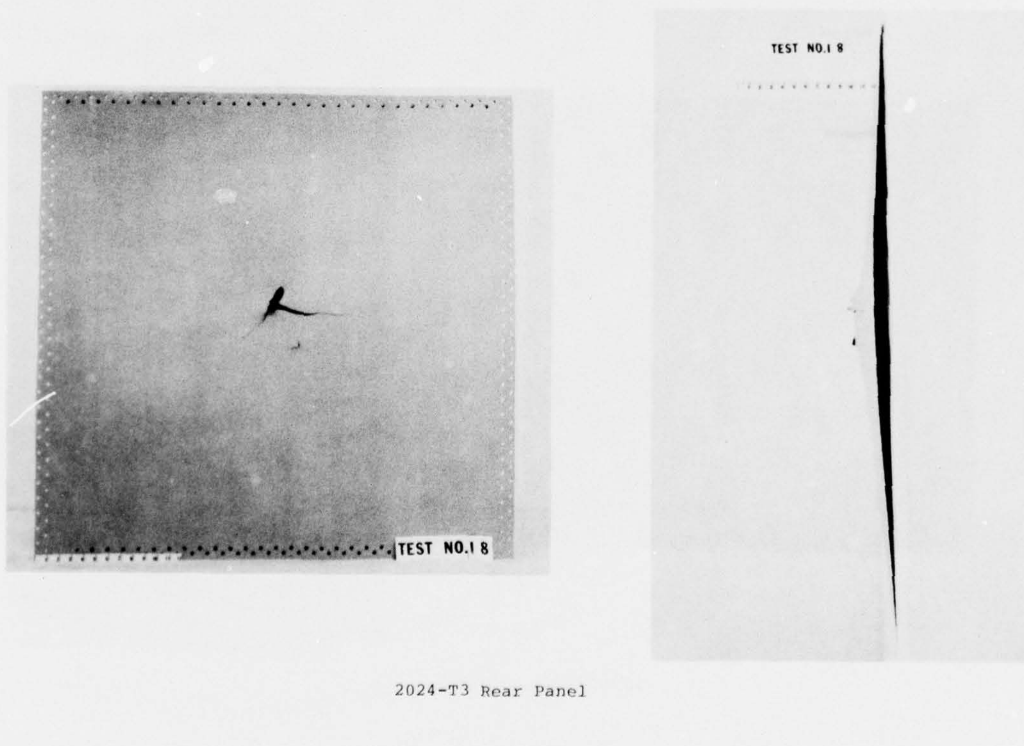


2024-T3 Rear Panel

Figure 25. Fragment Damage to Full Fuel Tank Panels, Test 17



Thicker 7075-T6 Front Panel



2024-T3 Rear Panel

Figure 26. Fragment Damage to Full Fuel Tank Panels, Test 18

impacted with only the high-velocity fragments. A front and a side view of the front and rear test panels are included for each test. These photographs were taken such that the plane view shows the front panel, as seen from the gun location and the side (perpendicular) view looks at the fuel tank from the side so that the gun would be located on the right side. The perpendicular view of the rear panel was photographed from the same side as the front panel while the plane view of the rear plate shows it as seen from behind the fuel tank, 180° from the gun location. Thus, the two pairs of photographs together show the fuel tank damage as seen from the front, one side, and the rear.

As can be seen on these photographs, the damage to the front target plates from the five fragments and the resulting hydraulic ram was very similar in all tests regardless of material used. Each target plate was penetrated by all five fragments and cracked in most cases from the center out towards the four corners. The primary difference in the cracking pattern was that the 7075-T6 plates had the tendency to have a larger number of cracks and the petal like segments formed did not protrude out from the plane of the plate as much as the ones of the 2024-T3 plates. In addition, on some of these tests a portion of the plate center was completely sheared off by the hydraulic ram around the perimeter of the fragment pattern.

Damage to the rear plate of the fuel target consisted of some permanent deformations of 2 to 3 inches (51 to 76 mm) and fragment damage that varied from five fragments penetrating to no penetrations with only small cracks on the "dimples" made by the fragments. Except for the tests that used the thicker 2024-T3 aluminum front panels, the fragment damage was very similar for all the other target combinations. The flow rates measured on Tests 13 and 14 emphasize this point. It is apparent that only the thicker

2024-T3 front panels offered enough resistance to penetration to decrease the rear plate damage and, thus, the flow rate.

The test matrix and the measured results of the eight combined loads tests performed on the full simulated fuel tank are presented in Table 8. Two experiments were conducted with each type of front target plate. The average velocities were, as expected, very close to the desired value averaging 4482 fps (1367 m/s). Figures 27-34 show the damage to the front and rear panels for these tests using the combination of five fragments and a blast wave impacting the simulated fuel tank.

In looking at these photographs and comparing the damage of the combined loads versus the load of the fragments alone, some very interesting observations can be made. First of all, the level of damage from the combined load to each type of front target plates with the full fuel tank is very similar to that of the corresponding plates tested with the fragments alone. One minor difference that can be observed is that the combined load appears to generate additional cracks (petals) from the center out towards the perimeter of the front panels. A second minor difference is that the radial cracks on the front plates sometimes did not propagate as far out to the edges with the combined load as with the fragments alone. The fact that the front plate was beginning to be loaded by the blast pressure approximately 3 msec after fragment impact, may have lessened the damage caused by the hydraulic ram thus causing shorter cracks to develop, but at the same time creating a differential loading that probably resulted in additional fractures to occur. Other than these two minor differences, the front and side damage photographs of the panels look quite alike for both the combined and fragments only loads.

Table 8. Full Fuel Tank Tests, Combined Loads

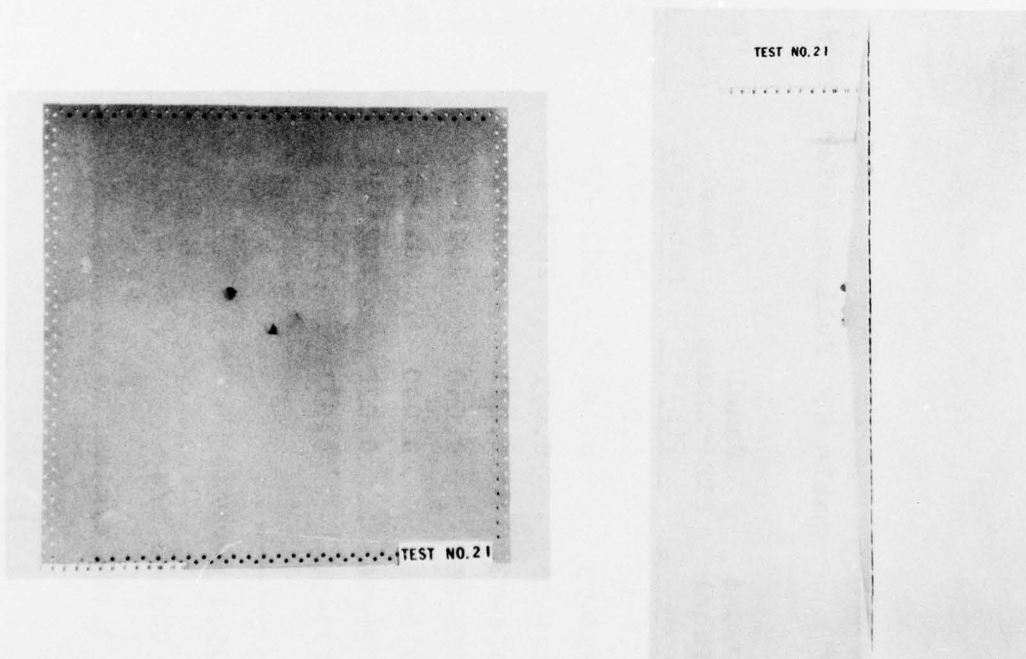
Test No.	Front Panel Material	Panel Thickness (in)[a]	Rear Panel Material	Panel Thickness (in)	Fragment Velocity (fps)[b]	No. Frags Penetrating Rear Wall	Rear Wall Flow Rate (gpm)[c]
21	2024-T3	0.040	2024-T3	0.10	4348	2	4.0
22	2024-T3	0.040	2024-T3	0.10	--	2	3.0
19	2024-T3	0.071	2024-T3	0.10	4557	3	3.0
20	2024-T3	0.071	2024-T3	0.10	4455	0	2.5
25	7075-T6	0.040	2024-T3	0.10	4642	5	Massive
33	7075-T6	0.040	2024-T3	0.10	4540	5	Massive
23	7075-T6	0.071	2024-T3	0.10	4440	0	4.2
24	7075-T6	0.071	2024-T3	0.10	4394	2	5.3

[a] 1 in = 25.4 mm

[b] 1 fps = 0.3048 m/s

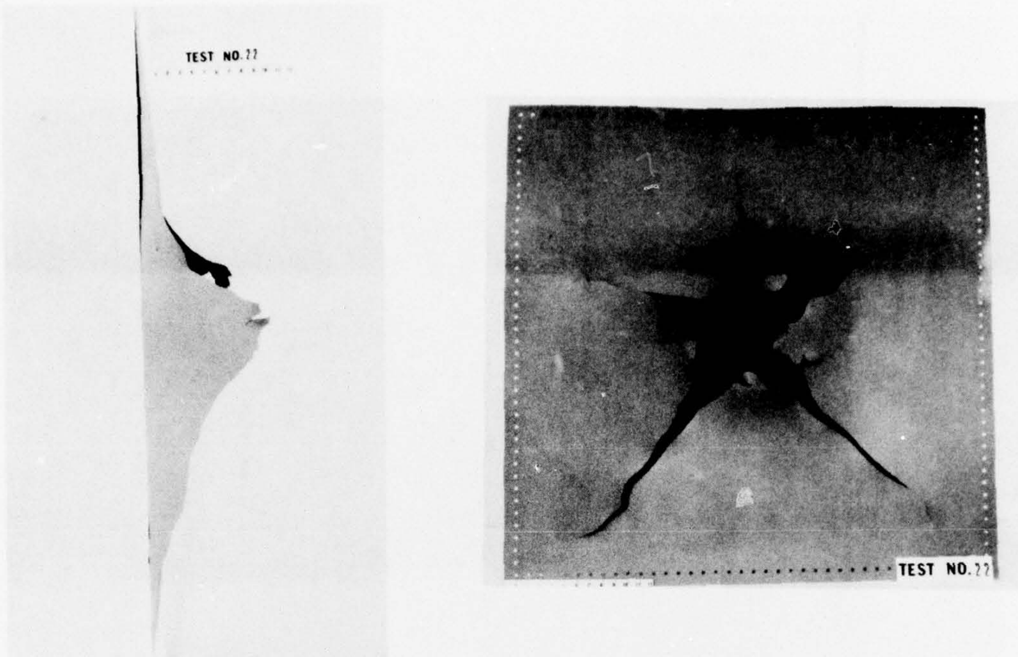
[c] 1 gpm = 3.785 ℓ/min

Thinner 2024-T3 Front Panel

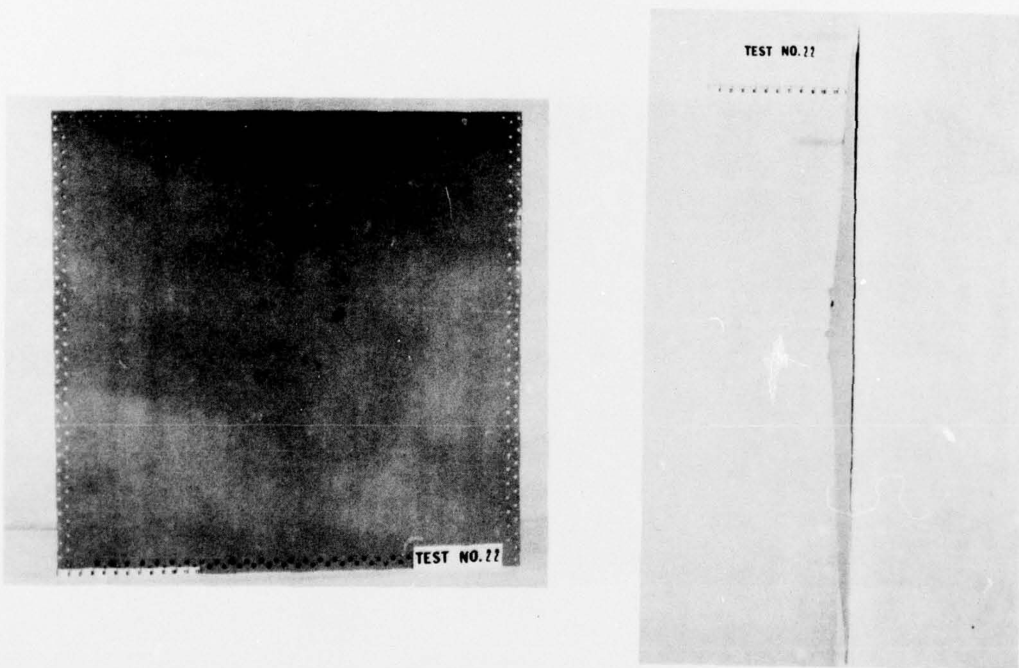


2024-T3 Rear Panel

Figure 27. Combined Fragment and Blast Damage
to Full Fuel Tank Panels, Test 21

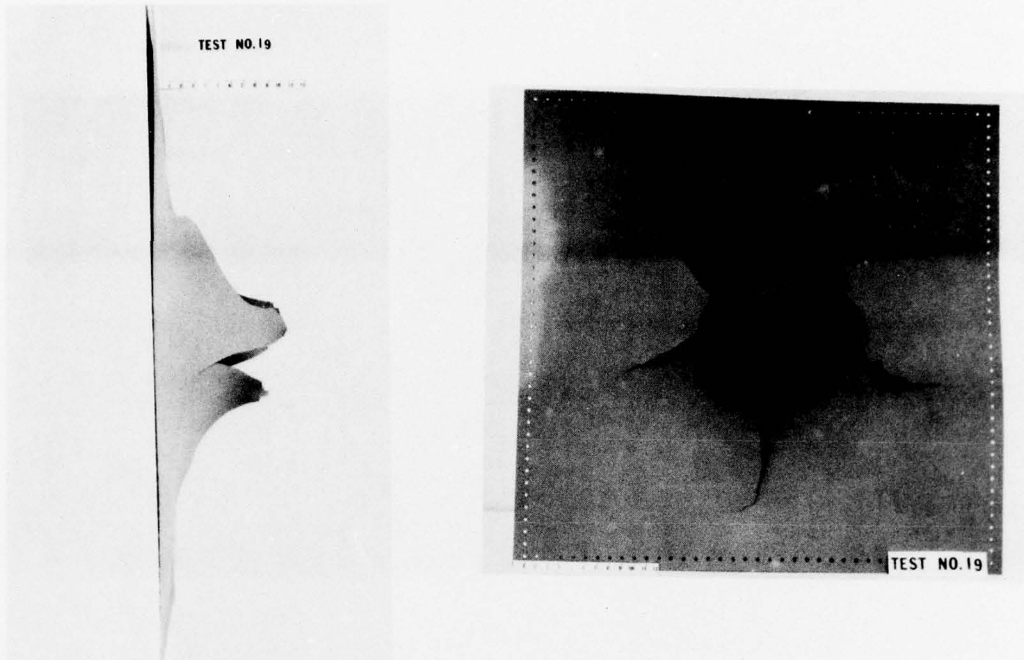


Thinner 2024-T3 Front Panel

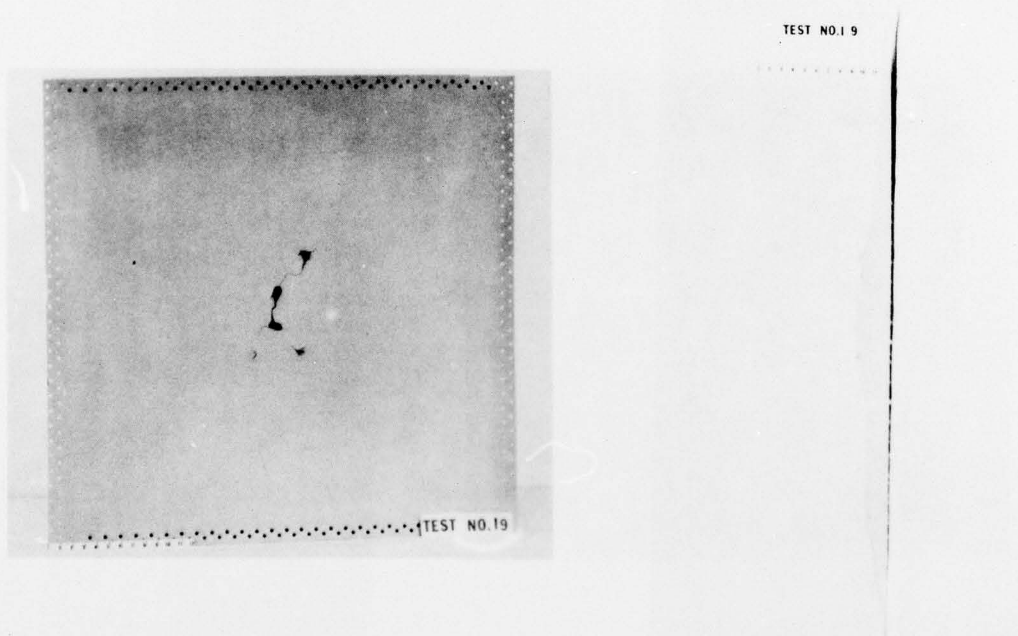


2024-T3 Rear Panel

Figure 28. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 22

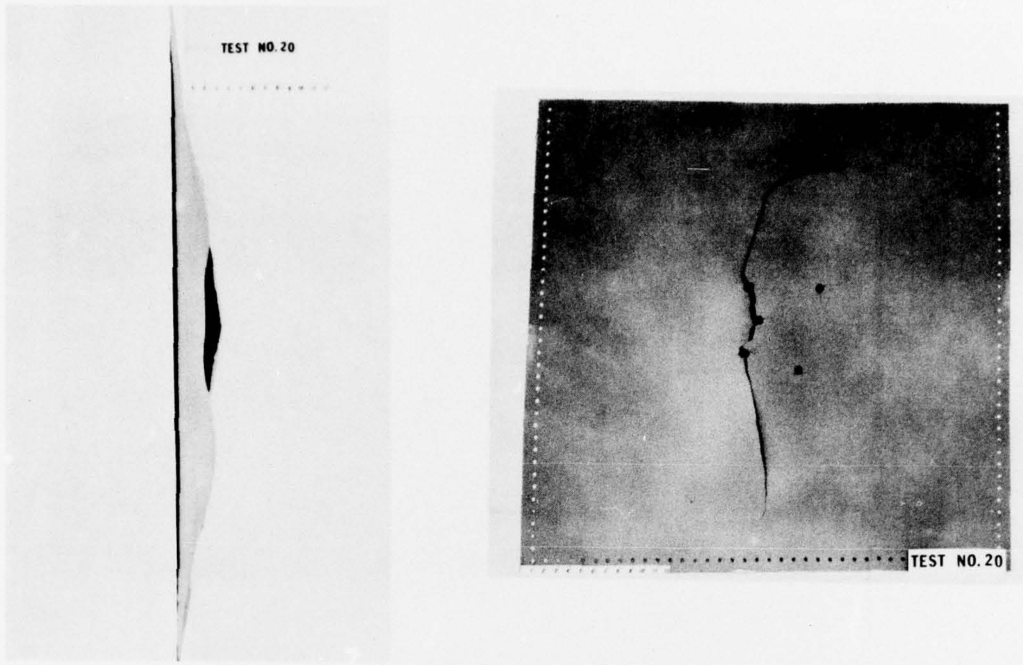


Thicker 2024-T3 Front Panel

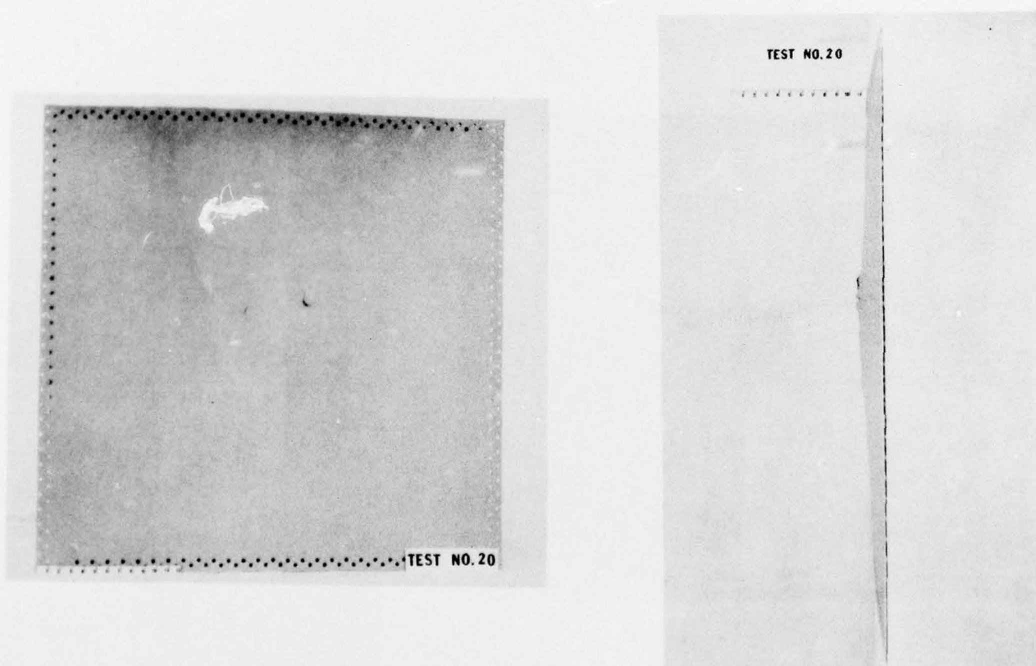


2024-T3 Rear Panel

Figure 29. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 19

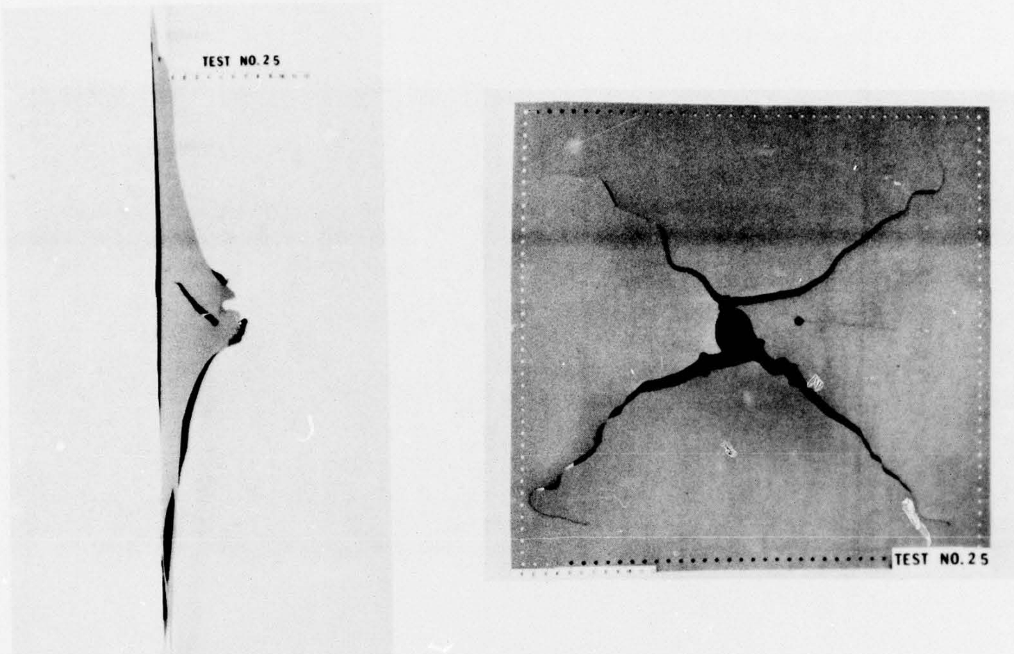


Thicker 2024-T3 Front Panel

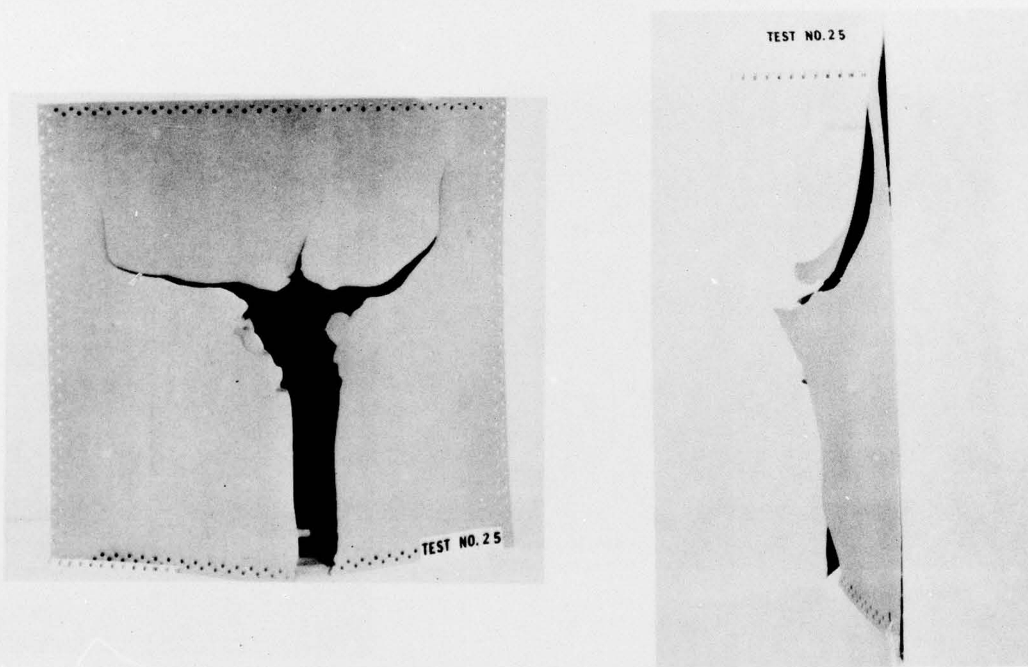


2024-T3 Rear Panel

Figure 30. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 20

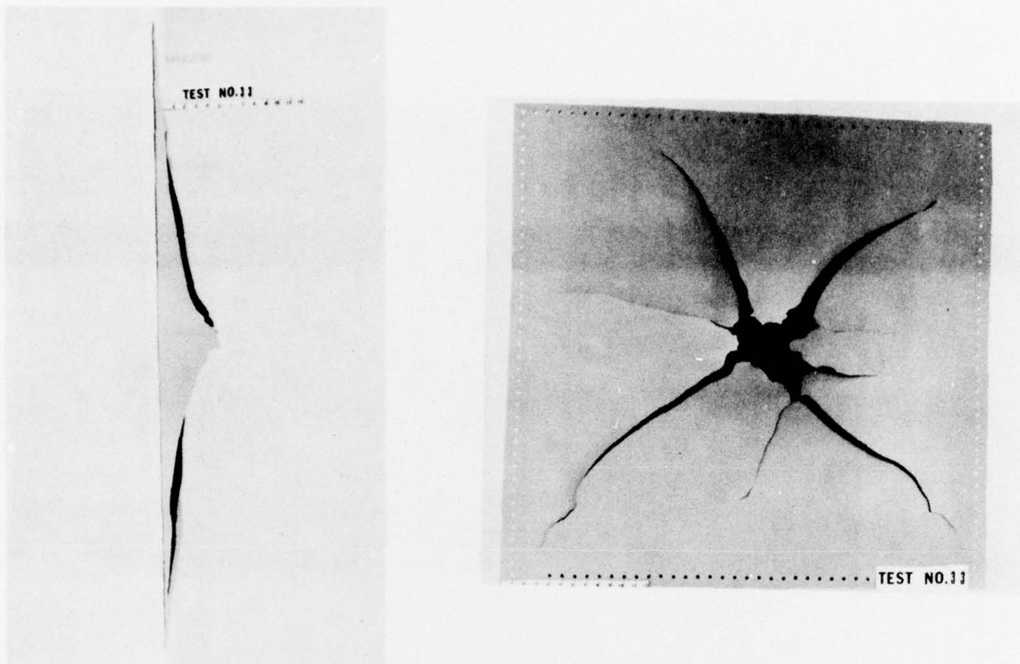


Thinner 7075-T6 Front Panel

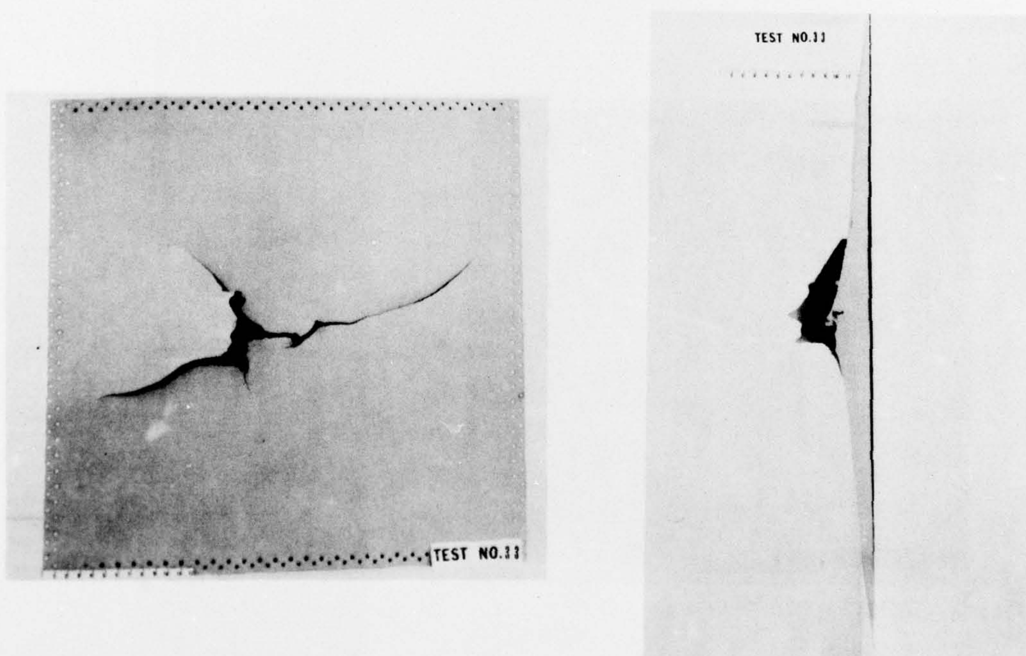


2024-T3 Rear Panel

Figure 31. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 25

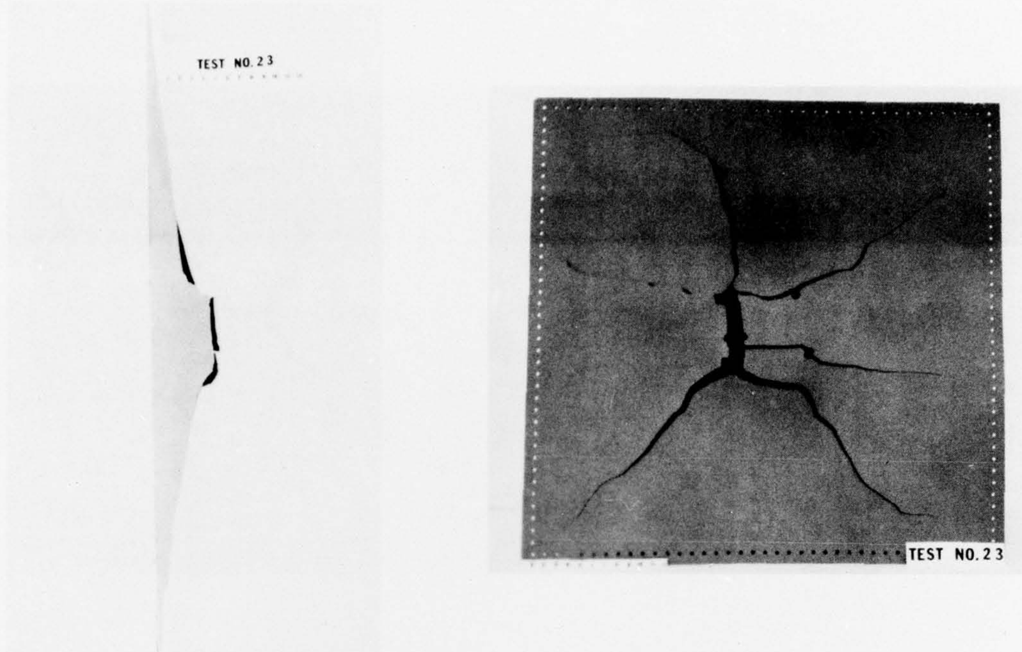


Thinner 7075-T6 Front Panel

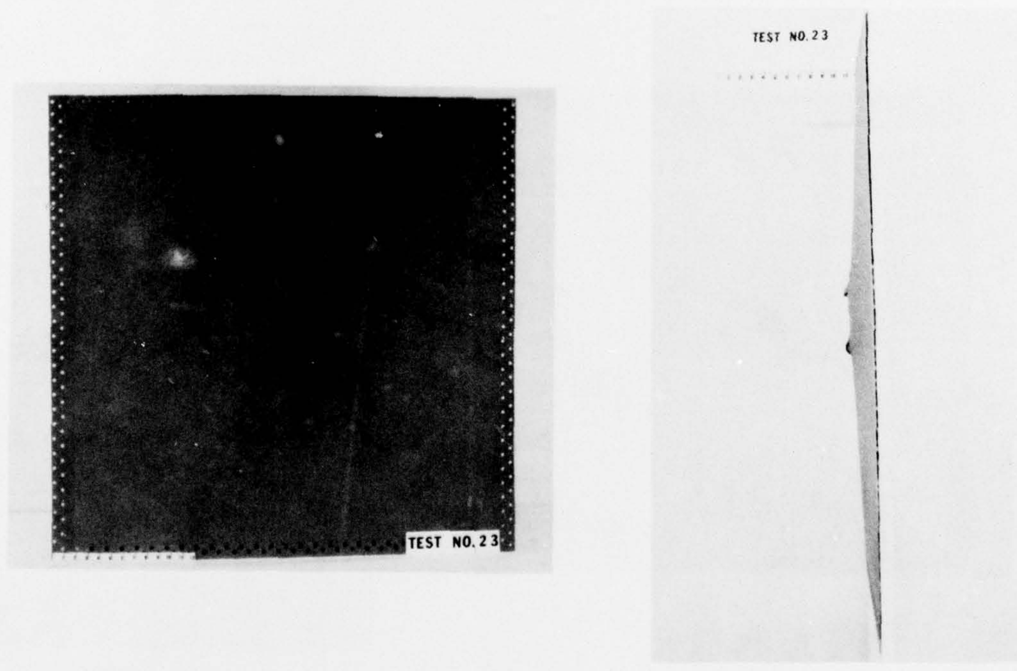


2024-T3 Rear Panel

Figure 32. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 33

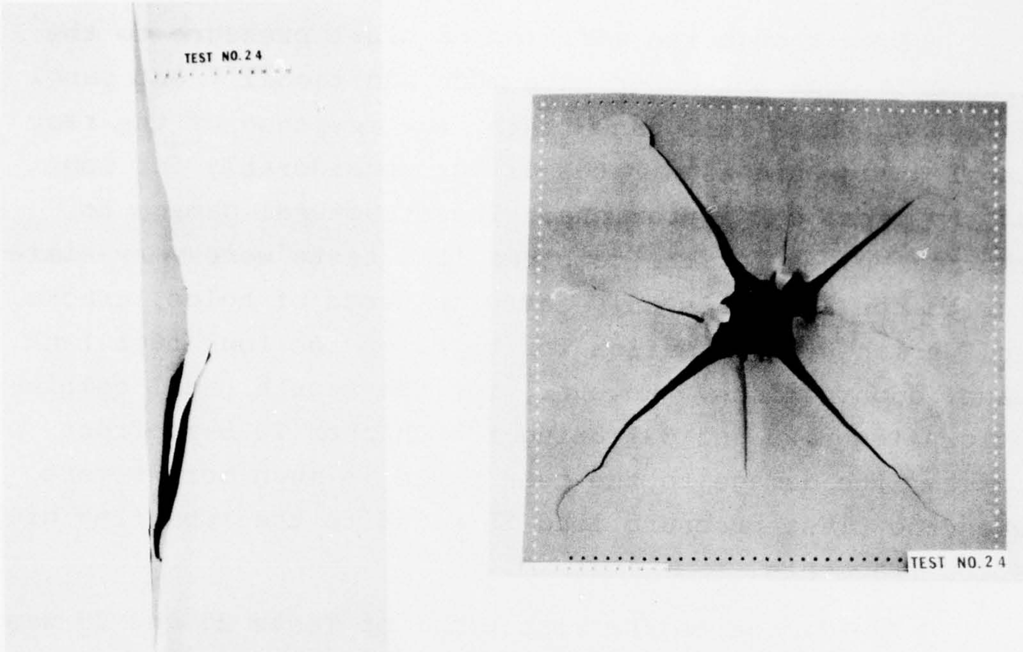


Thicker 7075-T6 Front Panel

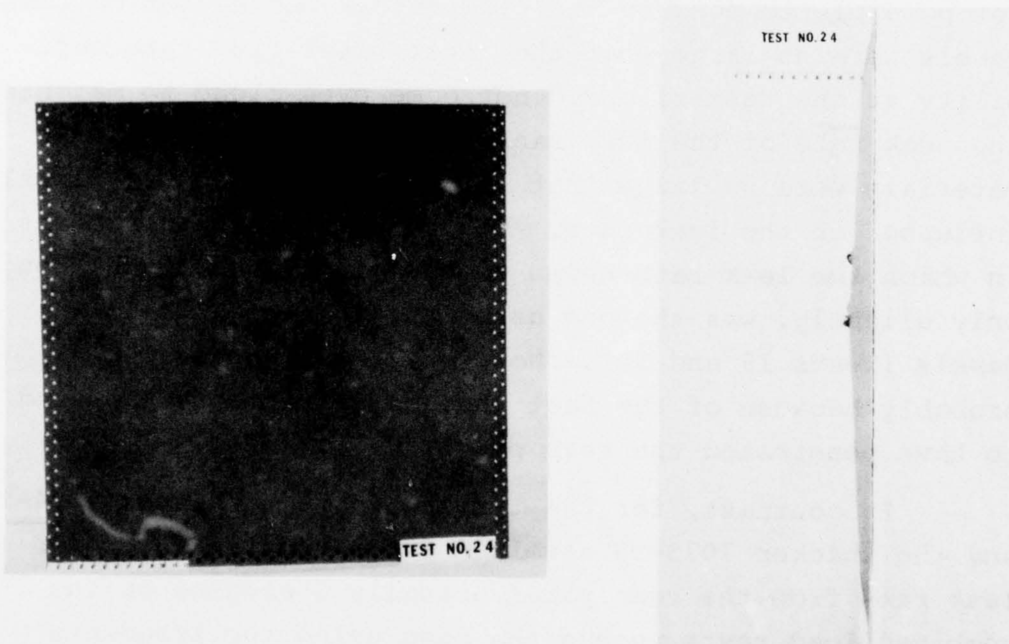


2024-T3 Rear Panel

Figure 33. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 23



Thicker 7075-T6 Front Panel



2024-T3 Rear Panel

Figure 34. Combined Fragment and Blast Damage to Full Fuel Tank Panels, Test 24

Even though the addition of blast pressure to the fragments does not contribute much additional front panel damage on these full tank tests, the response of the rear panel damage and flow rates differ considerably for some of the panel configurations. The structural damage to the rear plate for the combined load tests were very similar to the fragments only tests in terms of holes, cracks, and permanent deformation for three of the four fuel tank panel combinations. However, for the fourth panel combination (Tests 25 and 33) using the thinner 7075-T6 front panels, the damage to the rear plate is much more severe when the blast pressure load is added to the impacting high-speed fragments.

The damage to the rear panel of Tests 25 and 33 was so catastrophic because of the large cracks to the panels, and in one case, large numbers of screws shearing, it was not possible to measure the flow rate. The wounds on these panels were so large that the input water flow rate capability at the test site did not come even close to matching the leak rate of the fuel tank. The rips on the bladder materials were so large that in effect they had very little influence on the leak rate. The other set of experiments in which the leak rate seems to have increased, even though only slightly, was the one using the thicker 2024-T3 panels (Tests 19 and 20). However, this increase was probably because of the fact that more fragments happened to have penetrated the rear panel.

In contrast, for the tests using the thinner 2024-T3 and the thicker 7075-T6 aluminum front panels, the water leak rate from the rear panel actually decreased on the combined load tests versus the ones using the fragments alone. The reason for this is attributed to the final misalignment of the holes on the panel and bladder material caused by the resultant loading and stretching of the bladder material from the combination of the hydraulic ram and blast pressure loading.

IV. CONCLUSIONS AND RECOMMENDATIONS

Anti-aircraft missile warheads pose a severe threat to aircraft even when the missile misses the target and detonates in close proximity. Particularly vulnerable to the high-speed fragments and transient blast pressure loading are aircraft fuel tanks. Therefore, to evaluate aircraft designs and assess their vulnerability to such threats, simulated fuel tank tests are being performed, rather than conducting expensive prototype tests.

In this program, multi-fragment launching techniques were used with a blast simulator developed in an earlier program to generate a synchronized load to assess the enhancement from the blast loading to the damage caused by the simulated fragments from a missile warhead impacting a fuel tank.

Preparatory tests were conducted to develop the techniques for applying the combined load to the simulated fuel tank aluminum panels. These tests showed that the blast simulator would produce relatively uniform loading on the front panel when the explosive charge was moved off-center to allow passage to the five high-speed fragments. The length of time for the charge to detonate and for the blast wave generated to impinge the test panel was measured and trigger circuitry was made up to delay the time of blast loading approximately 3 msec after fragment impact. This fragment to blast loading delay can be changed experimentally to simulate other missile miss distances.

The preliminary tests showed that the desired average fragment velocity of 4500 fps (1372 m/s) was attainable and quite repeatable from test to test. Also, the fragment tests confirmed the expectation that the reticulated foam used in the blast simulator had a negligible effect on the fragment velocity. Therefore, no adjustment was necessary to the 30 mm case load for experiments using the blast simulator.

Sixteen experiments conducted used an empty simulated fuel tank with four different types of aluminum target panels. These tests used only the front panel on the fuel tank. Nine of these experiments were done by firing only the five fragments against the fuel tank. The other seven tests used the combined fragment and blast pressure load. The results show that the addition of blast pressure enhances considerably the damage caused by the fragments. Gross structural failure was particularly evident on the 7075-T6 aluminum panels of two thicknesses, 0.040 and 0.071 in. (1.02 and 1.80 mm) and the 0.040 in. (1.02 mm) thick 2024-T3 panel. Catastrophic structural failure was resisted only by the 0.071 in. (1.80 mm) thick 2024-T3 panels tested. However, even these more resistant panels sustained large cracks near the center of the target and were visibly permanently deformed as a result of the addition of the blast pressure to the high-speed fragments.

The 17 similar experiments performed with a full fuel tank produced some very interesting results. These experiments used the same type of front target panels on the fuel tank as the empty tank tests. For the rear wall of the fuel tank 0.10 in. (2.54 mm) thick, 2024-T3 aluminum panels were used on all full tank tests. Damage to corresponding front panels was very similar for all tests regardless of whether the blast pressure was used or not. Only minor differences in the structural damage to the front plates were evident. The combined load seems to cause a few more cracks on the panels but the cracks sometimes did not propagate out to the edges as much as the ones tested with fragments only.

The addition of the blast pressure resulted in very similar structural damage to the rear panel for all combinations except one. On the tests using the thinner 7075-T6 front panels, the damage to the rear panels was considerably greater than by the fragments alone. Large cracks and some

panel rip-out to these rear plates resulted in a massive flow rate (fuel ingestion) out the wounds of these panels. For the other panel combinations, the water leak rate increased slightly in one and decreased somewhat on the other two probably due to the effects of the blast pressure on bladder material misalignment and stretching.

The results of this limited experimental program using a simulated fuel tank show that on an empty tank, damage to front target panels is enhanced considerably by the addition of a transient blast pressure to multiple high-speed fragments. On the other hand, with a full tank the addition of the blast pressure loading does not significantly enhance the damage to the front panels. Damage to the rear panels was similar on three of the four panel combinations. However, on the fourth combination using the thinner 7075-T6 front panels, catastrophic rear panel structural damage resulted by the addition of the blast pressure loading.

The results presented here indicate that although for some of the test configurations the addition of blast pressure did not enhance fuel tank damage, enhancement occurs in others to a very high degree. Consequently, it is recommended that the blast threat be included in future vulnerability testing of simulated fuel tanks or other aircraft components to accurately simulate, near-miss, warhead detonation environments. Also, because only the two extremes of empty and full fuel tanks have been tested to date with the coupled blast and fragment load, it would be worthwhile in the future to conduct additional tests with a partially filled simulated fuel tank to determine the damage enhancement due to the addition of the blast wave. Damage to rear panels, as well as leak rates, of such tests may very well be quite a bit more severe than that for full tank tests reported here and failure mode for the front panels will probably differ from both the empty and full tank tests.

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